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Effects of Multisensory Stimulation in Virtual Reality

DIPLOMA THESIS

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in

Media and Human-Centered Computing

by

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Advisor: Ao.Univ.Prof. Mag. Dr. Horst Eidenberger

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B.Sc. Sebastian Reissmüller

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Wien, 22. November 2024

Sebastian Reissmüller

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Ich möchte mich bei meinem Betreuer Prof. Dr. Horst Eidenberger für die Flexbilität, den Optimismus und die allgemeine Unterstützung bedanken. Desweiteren möchte ich mich bei meinen Kolleg:innen vom CSD für ihr Verständnis und ihre Unterstützung bedanken. Ich möchte auch die unglaubliche Arbeit von Forschern wie Lanier, Slater und Palmer würdigen, die mit ihrer Vision den Grundstein für den Bereich der VR gelegt haben.

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Kurzfassung

Die vorliegende Arbeit befasst sich mit den Auswirkungen der Integration von multisensorischen Feedback, insbesondere der Kombination von 3D-Audio und haptischen Elementen. Im Rahmen der Studie wurde der Einfluss auf die Kernmetriken 'immersion', 'presence' und 'motion sickness' untersucht. Die vorliegende Untersuchung schließt eine Lücke in der bestehenden Forschungsliteratur zum Thema Virtual Reality, indem sie die Auswirkungen von synchronisiertem sensorischem Feedback auf die Benutzererfahrung über den Bereich der visuellen Immersion hinaus untersucht. Zu diesem Zweck wurde das VR-System 'Phantastic Sound Experience' entwickelt. Das System verbindet 3D-Audio mit taktilem Feedback, indem es eine virtuelle Umgebung mit einem eigens dafür angefertigten Konstrukt kombiniert, welches audio-ausgelöste taktile Vibrationen erzeugt. Im Rahmen der Evaluierung des Projekts wurden zwei Versionen des Systems getestet, um eine Gegenüberstellung der Ergebnisse zu ermöglichen. Die Datenerhebung erfolgte mittels standardisierter Fragebögen zur Erfassung der Präsenz- und Immersionserfahrung sowie durch leitfadengestützte Nutzerinterviews. Die Implementierung multisensorischen Feedbacks resultierte in einer leichten Intensivierung der 'immersion' und 'presence' der Testpersonen. Die Teilnehmer:innen der Gruppe B, welche sowohl taktiles als auch akustisches Feedback erhielten, berichteten über eine verstärkte körperliche Reaktion sowie eine Verringerung der Wahrnehmung der realen Welt. Während bei einigen Messwerten keine statistisch signifikanten Unterschiede festgestellt wurden, deutete qualitatives Feedback auf ein stärkeres Gefühl der Zeitverzerrung und der 'presence' bei denjenigen hin, welche multisensorische Hinweise erhielten. Die Ergebnisse legen nahe, dass die Kombination von 3D-Audio und haptischen Reizen in VR das Potenzial birgt, die Nutzerbindung zu intensivieren. Dennoch sind weitere Forschungsarbeiten erforderlich, um die für die Integration der sensorischen Reize eingesetzten Techniken zu verfeinern. Die vorliegende Studie präsentiert Erkenntnisse zur effektiven sensorischen Synchronisation in VR und identifiziert Forschungsfelder für künftige Untersuchungen. Dazu zählen die Optimierung von Kalibrierungsmethoden für haptisches Feedback sowie die Analyse individueller sensorischer Wahrnehmung. Die Resultate dieser Studie bilden die Basis für weitere Projekte die multisensorische Stimulierung einsetzen, um ein umfassendes immersives Nutzerlebnis ermöglichen.

Abstract

This thesis investigates the impact of integrating multisensory feedback, particularly the combination of 3D audio and haptic elements, on the enhancement of immersion and presence in virtual reality environments. Addressing a significant gap in the existing VR research literature by examining the impact of synchronized sensory feedback on user experience, extending beyond the domain of visual immersion. To investigate this, the "Phantastic Sound Experience" VR system was developed. The system is implemented to combine 3D audio and tactile feedback by combining a virtual environment with a custom built physical device, that provides audio-triggered tactile vibrations. The participants were exposed to two conditions: one incorporating multisensory feedback and another comprising solely the visual environment. Quantitative and qualitative data were gathered through the administration of standardized presence and immersion questionnaires, complemented by user interviews. The findings indicate that the provision of multisensory feedback has the effect of enhancing user immersion and presence. In particular, those in Group B (who received tactile and audio feedback) reported increased physical involvement and a reduction in their awareness of the real world. While no statistically significant differences were observed in some metrics, qualitative feedback indicated a stronger sense of time distortion and "being there" among those receiving multisensory cues. These findings imply that the combination of 3D audio and haptics in VR has the potential to enhance user engagement. However, further research is required to refine the techniques employed for the integration of sensory stimuli. This study provides insights into effective VR sensory synchronization and identifies areas for future work, such as the optimization of calibration methods for haptic feedback and the examination of individual sensory processing differences. These findings establish a foundation for nuanced sensory synchronization in VR, advancing design strategies that foster fully immersive user experiences.

Contents

CHAPTER 1

Introduction

1.1 Motivation

Virtual Reality (VR) technology has developed rapidly from a concept initially situated in the realms of science fiction to a medium with a range of applications across various domains, including entertainment, education, and healthcare. The potential of VR to create immersive and engaging experiences has led to considerable developments in hardware, particularly in the area of high-resolution and low-latency head-mounted displays. The author thinks that despite these advances in visual technology, the pursuit of a fully immersive experience has often overlooked the critical role of other sensory modalities, such as spatial audio and tactile feedback. Despite these advancements, current VR technology also faces challenges such as high costs, technical limitations like latency and resolution issues, and potential side effects such as motion sickness. Future developments aim to address these limitations and expand VR's accessibility, potentially making it as ubiquitous as personal computers or smartphones in daily life [32].

Recent research has highlighted the significance of these non-visual sensory inputs in developing a more comprehensive and immersive experience. A systematic review by Melo et al. [53] indicates that the incorporation of multisensory stimuli, such as auditory and haptic feedback, substantially enhances user engagement and the sense of presence in virtual environments. Their findings suggest that combining multiple sensory modalities can create a more realistic and immersive virtual reality experience, improving user interaction and overall satisfaction. This underscores the importance of integrating various sensory inputs to simulate real-world experiences more effectively.

The integration of spatially accurate audio cues, achieved through techniques such as binaural audio, has been demonstrated to significantly contribute to the development of spatial awareness and presence within virtual environments. Such auditory cues not only enhance the overall immersive experience but also provide crucial information for orientation, proximity, and environmental context [88]. Furthermore, the incorporation of tactile feedback mechanisms, such as haptic devices and vibrations, introduces a physical dimension to virtual experiences, enabling users to perceive interactions, textures, and environmental nuances. This tactile interaction serves to enhance the realism and engagement of virtual reality environments, thereby blurring the line between the virtual and physical worlds.

Although significant advances have been made in the visual field of VR systems, the potential of auditory and tactile feedback remains under-researched. The current generation of VR technologies tends to prioritize visual stimuli, with an emphasis on high-resolution displays and advanced graphics. While these elements are crucial, they do not fully leverage the potential of multisensory input to achieve a truly immersive experience [54]. These insights highlight the importance of investigating the role of these additional sensory modalities in user immersion and presence, particularly in applications that require high levels of engagement, such as psychological and medical interventions. The importance of presence-inducing media for mental health applications has been demonstrated by research, with significant influence on therapeutic outcomes identified [79].

This thesis seeks to address this gap in research by investigating the impact of auditory and tactile feedback in virtual environments. By focusing on the integration of these non-visual sensory inputs, this study aims to provide new insights into enhancing user immersion, presence, and emotional engagement in VR, contributing to the development of more effective and immersive virtual experiences.

1.2 Problem statement and aim of work

The fundamental research conducted by Slater and Wilbur [68] established the significance of sensory stimuli in enhancing the sense of immersion and presence within virtual reality environments. Subsequent studies by Cooper et al. [20] and Shaw et al. [66]. provided further evidence of the significant impact of auditory and tactile stimuli on the user's sense of presence. Moreover, Bruun-Pedersen et al. [15] investigated the influence of auditory and tactile feedback, yet could not substantiate a notable impact of the sensory feedback. Given that the approach employed involved tasks and changing landscapes, the author believes that the impact of sensory input could be tested with different parameters, such as the user being passive in a more static environment. It is possible that these parameters may influence the outcome of the experiment. While the impact of sensory feedback in virtual reality is a topic of considerable research interest, relatively few studies have explored the combined effects of spatial audio and tactile feedback, which could enhance the immersive quality of the experience. Further investigation may therefore be beneficial to assess the impact of these techniques on the overall experience of virtual reality. This thesis seeks to address the aforementioned gap by conducting a systematic investigation into the effects of integrating binaural audio and tactile feedback in virtual reality environments. The following research questions will provide the framework for this study:

The primary objective of the authors research is to investigate the impact of integrating binaural audio and tactile feedback in a virtual environment on the user experience. The objective is to address the following research questions:

Research Question 1: How does the integration of 3D-audio and tactile stimuli influence levels of immersion and presence in a VR environment?

Research Question 2: To what extent do these sensory inputs have an impact on perceived motion sickness?

Research Question 3: What is the impact of sensory feedback on users' emotional states and the perceived pleasantness of the VR experiences?

The primary objective of this research is to address these questions, which serve to establish the fundamental premise that multisensory feedback can positively influence the key performance indicators for virtual reality experiences.

1.3 Methodological approach

In order to evaluate the impact of sensory feedback in virtual reality, a structured methodology was adopted. This methodology is focused on the creation of logically related physical and virtual systems, the iteration of user tests, and the comprehensive evaluation through participant studies. The following presents a comprehensive overview of the methodology employed, from the initial development of prototypes to the final implementation and the subsequent study of participants. The methodology places particular emphasis on the enhancement and assessment of sensory feedback mechanisms.

Literature review: The initial stage of the methodology involved a comprehensive literature review, which examined existing research and studies related to the effects of binaural audio and sensory feedback in virtual reality. This review provided a robust foundation by summarizing and integrating current knowledge in the field. Given the recent surge in VR research across various disciplines, the literature review highlighted recent studies that offer valuable insights and a frame of reference for this project.

Development of a prototype: Once the literature review was complete, the next phase of the project was to create a prototype for use with virtual reality technology that incorporated binaural audio and sensory feedback. This practical implementation allowed for hands-on experimentation, thereby enabling the assessment of the feasibility and effectiveness of the proposed technologies.

Usability testing: Prior to the final implementation, the prototype was evaluated through a usability test. This phase proved instrumental in enabling the system to be refined in accordance with the feedback provided by users. A small number of participants tested the prototype, providing feedback regarding the virtual world, sound and overall appeal. The iterative process of testing and refinement ensured that the prototype was adequately prepared for the subsequent user-based evaluation.

Evaluation and analysis: The final phase of the study involved a user-based evaluation, in which participants engaged with the VR prototype in a controlled study. The participants were divided into two groups and completed questionnaires designed to measure their experiences with spatial audio and sensory feedback. The questionnaire was based on insights from previous research, including the Igroup Presence Questionnaire and the Immersion Tendencies Questionnaire. The evaluation provided valuable feedback and observations in order to evaluate the effectiveness of the sensory feedback mechanisms employed.

This structured methodology allowed for a thorough exploration and assessment of the impact of sensory feedback in VR, contributing to the development of more immersive and realistic virtual environments.

1.4 Thesis structure

The structure of the thesis is designed to provide a comprehensive examination of the theoretical foundations, practical implementations, and an empirical evaluation.

The second chapter presents a review of the existing literature on virtual reality and related work, offering a detailed explanation of the key concepts of VR. The chapter opens with an overview of the application and historical developments as well as current advancements of VR. Subsequently, the key dimensions including presence, immersion, motion sickness, and emotions, are examined in detail. Subsequently, the chapter examines the function of sensory feedback in VR, with a focus on visual, auditory, and tactile feedback mechanisms.

The following chapter will present the design and concept of the virtual reality system. This entails outlining the system's requirements, the design approach, and the system conception. This chapter will examine specific elements of the system, including the virtual environment, spatial audio and tactile feedback, and will explain the methodology employed in developing each component and integrating them into the system.

The following section will present an outline of the development process. It covers the design and integration of the virtual world, including the creation of digital assets, the implementation of the previously mentioned design in Unity, and the incorporation of visuals and sound. Additionally, the construction and integration of the hardware for tactile feedback are described, along with technical aspects such as the physical component and integration of the vibration module.

The evaluation chapter provides an overview of the conduction and analysis of the user study. This chapter reflects on the objectives discussed in the first chapter, evaluates the effectiveness of the methodology employed, and discusses the implications of the findings.

In the last chapter the author reflects on the challenges of the project and identifies potential of future developments.

CHAPTER 2

Literature review

In this chapter the key aspects of virtual reality will be examined, including its applications, historical development, and current technological landscape. The first section provides an overview of VR applications in sectors such as gaming, healthcare, robotics and manufacturing. We then delve into the history and present of VR, exploring the milestones that have shaped its development from the 1960s to the present day. The section is followed by the analysis of the critical components of VR systems, including the hardware and sensory feedback mechanisms that play a key role in creating immersive experiences. Finally, the chapter concludes with an assessment of related work and key factors that influence the effectiveness of VR, setting the stage for the research objectives of this thesis.

2.1 Overview of Virtual Reality

Virtual Reality has evolved rapidly as a transformative medium, offering immersive experiences beyond traditional interaction methods. Its applications cover a wide range of fields such as entertainment, education and health care, providing users with unique opportunities to interact with digital environments that were previously unimaginable. This chapter focuses on the fundamental concepts of VR technology, its applications and describes in detail the main components that make up the VR system.

2.1.1 VR applications

With a novel way to interact in a virtual space VR shows potential to branch into different areas of application. Although the immersion of users in virtual environments is primarily a visual experience, it also has spatial awareness-enhancing and interactive capabilities. This allows users to interact with these virtual environments as if they were the real thing, which has significant implications for how we understand the boundaries between reality and fiction. As noted by Hamad and Jia [32], "VR has the potential to be a highly beneficial tool in a variety of applications and across a wide range of fields", including education, healthcare, gaming and engineering. Furthermore, Javaid and Haleem [42] emphasize the utility of VR across industries, describing it as "a promising technology that is finding its place in a range of fields, including manufacturing, education, and medical applications."

Gaming has been one of the earliest and most prominent sectors to adopt VR technology, bringing a new level of interaction to digital entertainment. VR games allow players to immerse themselves in virtual experiences where they can explore, manipulate objects and control their surroundings through intuitive, natural movements. The level of engagement offered by VR enhances the gaming experience, giving players a stronger emotional connection to the gameplay and story. Platforms such as Oculus Rift, HTC Vive and PlayStation VR have made VR gaming more accessible, with a wide range of titles from high-action shooters to puzzle and exploration games. The high-fidelity graphics, spatial audio, and advanced haptics work together to create an immersive environment that sets VR gaming apart from traditional experiences. VR is making significant contributions to the medical field, particularly in training, diagnosis and therapy. "VR allows medical students and professionals to practice complex procedures in a risk-free, controlled environment," as Hamad and Jia [32], explain. Surgical simulations, for example, provide a realistic hands-on experience that helps practitioners hone their skills without the need for real patients. Javaid and Haleem [42] elaborate on this, noting that VR "enhances the precision and skills of medical professionals through detailed surgical simulations". In therapeutic settings, VR is also used in exposure therapy for anxiety and post-traumatic stress disorder (PTSD), allowing patients to confront fears in a controlled environment. In physical rehabilitation, VR is used to help patients regain motor function through interactive exercises that monitor progress and motivate engagement.

In robotics, VR serves as a powerful tool for training and control systems. VR creates virtual representations of physical environments, allowing operators to remotely control robots with precision while visualising real-time data in a simulated 3D environment. This is particularly valuable in industries such as space exploration and defence, where robots are used in dangerous or inaccessible environments. "VR enables more intuitive human-robot interaction by allowing operators to manipulate virtual robots in real time," improving accuracy and reducing operational errors. Javaid and Haleem [42] also point out that "virtual environments in robotics training allow for better control of complex tasks, reducing errors and increasing safety".

The production and manufacturing sector is also benefiting from VR, which is being used to "optimize workflows, improve training and enhance product design". VR simulations allow engineers and managers to design and test production lines before physical implementation, reducing costs and helping to identify inefficiencies early in the process. Hamad and Jia [32] note that "VR facilitates collaborative design by allowing team members to interact with virtual prototypes in real time" and make changes to product designs, even when they are remotely located. VR-based training programmes also help workers familiarise themselves with machinery and safety protocols in a virtual space, reducing on-the-job risks and improving overall efficiency.

The successful application of VR in these industries relies on the seamless integration of several key components that form the foundation of VR systems. In the next section, these components will be explored and explained how they work together to create immersive, interactive environments.

2.1.2 System components

A virtual reality system comprises essential key components that collectively facilitate the creation of an immersive and interactive digital environment. At the core of this system is the VR headset (C), which typically includes high-resolution stereoscopic displays for each eye. These are designed to deliver a three-dimensional visual experience by simulating depth perception. Such headsets are frequently furnished with accelerometers, gyroscopes, and magnetometers, which enable the accurate tracking of head movements. This allows for real-time adjustments to the user's viewpoint within the virtual space, which is vital for maintaining a coherent sense of presence and minimizing discomfort such as motion sickness. A further essential component is the tracking system (A), which captures the user's spatial movements and orientation. This system may employ external sensors or cameras, as exemplified by the HTC Vive system, or alternatively, it may rely on internal tracking mechanisms embedded within the headset, as observed in devices such as the Oculus Quest. The computational unit (E), which may take the form of a high-performance computer, gaming console, or integrated processing unit, is responsible for rendering the virtual environment, processing real-time user inputs, and ensuring seamless operation in order to support a fluid and responsive VR experience. The computational device must be connected to the HMD via suiting cables, mostly Display-link and USB-C (D). Furthermore, input devices (B), such as handheld controllers, haptic gloves, or motion sensors, facilitate user interaction with and manipulation of virtual objects, thereby enhancing the interactivity and engagement of the VR experience. The aforementioned components collectively constitute a unified system that serves as the foundation for the functionality of VR [87]. In addition, a working area (F), which encompasses the spatial boundaries of the virtual world, must be defined. This system enables users to fully immerse themselves in digitally constructed environments and interact with them in a manner that is intuitive and natural.

The core of VR technology is built on three interconnected concepts: immersion, presence, and interaction. The term "immersion" is used to describe the capacity of a virtual reality system to encourage the user to engage with sensory information in a way that is perceived as being real. Presence is the psychological phenomenon in which users perceive themselves to exist in a virtual environment rather than in a physical one. Interactivity measures the extent to which users can influence and react to the virtual world, thus improving the sense of realism and engagement [39]. These elements are fundamental to the ability of VR to create rich and interactive experiences in various fields, from games to therapeutic applications. Understanding these core concepts is vital not only

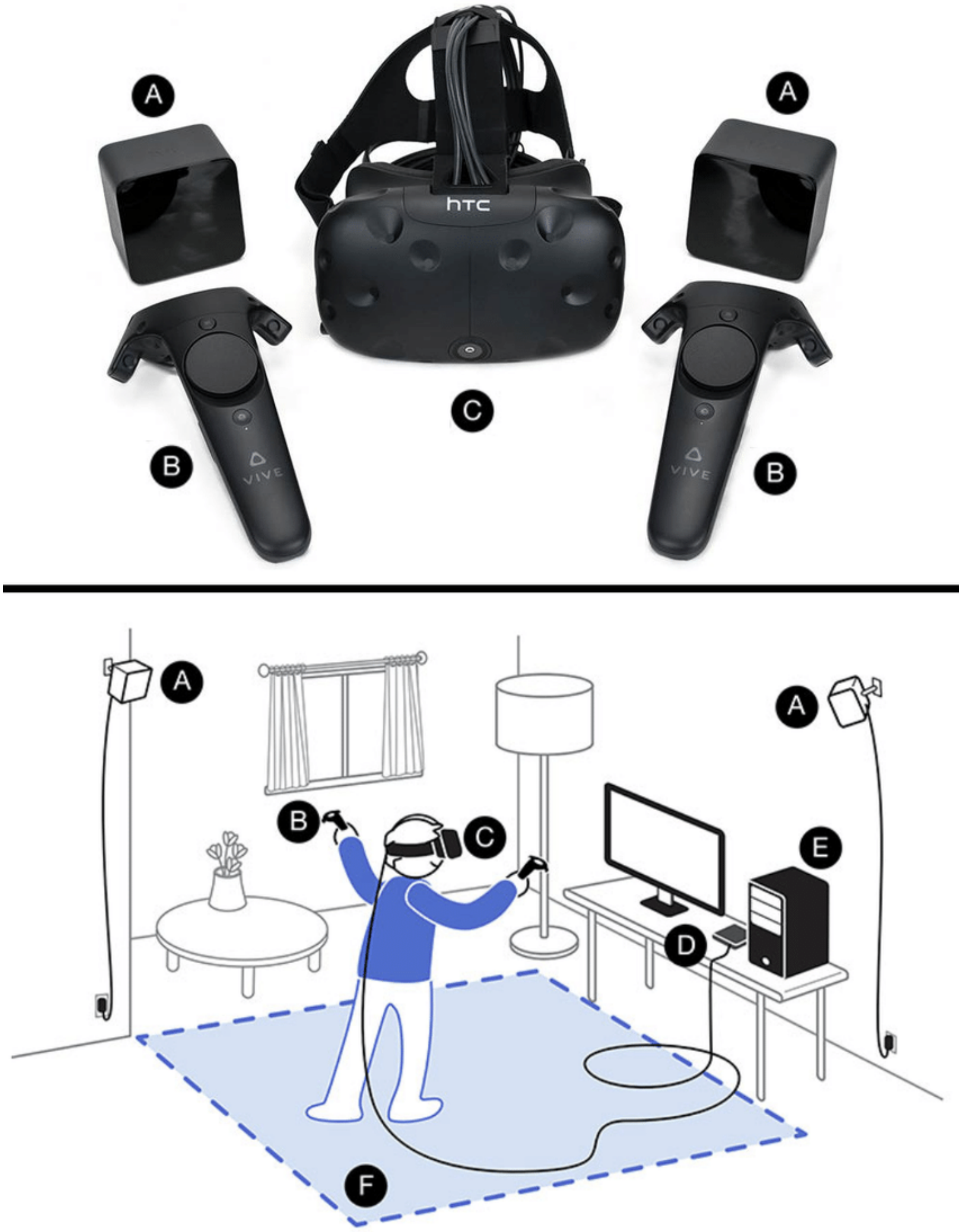


Figure 2.1: Key components of a VR setup [71]

to understand the capabilities and limitations of current VR technologies, but also to identify potential areas of innovation and improvement. After introducing the basic concepts of VR, the following sections will delve further into the historical evolution of this technology, its current state and the critical components that form a VR system.

Understanding the current technological capabilities of VR requires a look at the path it has followed. In the following section, the history of VR will be traced from its early conceptual roots to the advanced systems of today, providing context for its present-day applications

2.2 History and present of VR

The development of virtual reality technology is marked by significant milestones, which have gradually shaped its current form over the decades. The concept of VR goes back to the 1960s, when Sutherland [69] introduced the concept of Ultimate Display in 1965, whose concept was a virtual world in which users could interact with a head-mounted screen (HMD) This conceptual framework laid the foundations for the development of early VR systems. In the late 1960s, Sutherland and his student Bob Sproull created the first HMD, known as Damocles' sword. Although primitive in current standards, this device was a pioneer of virtual experience immersion [70].

Figure 2.2: The data glove by Lanier [81]

In the 1980s the introduction of VPL Research's Data Glove, founded by Jaron Lanier, made further advances. Lanier is recognized for popularizing the term "virtual reality" and is considered one of the pioneers in this field. His vision and work influenced the direction of VR technology. The data glove (shown in figure 2.2) allows users to interact with virtual objects with hand gestures, which paved the way for more interactive VR systems [6]. Lanier's contributions go beyond hardware, exploring the philosophical and social impacts of VR, and highlighting the potential of VR to expand human experience and creativity [48].

In the 1990s, VR became popular in commercial systems such as virtuality arcade machines and Sega VR headsets. However, these initial attempts were limited by technology constraints at the time, such as low-resolution displays, limited processing power, and high costs, which prevented widespread adoption. Despite these limitations, major research was conducted in the 1990s on the potential application of VR beyond gaming, including its use in training simulations, medical therapy and architectural design [13].

The following period has witnessed significant advances that have driven VR from a niche technology to a more common application. In the early 2000s, VR research focused on improving user interaction and realism. Developments in motion tracking technology, such as the introduction of optical tracking systems, have enabled more accurate and receptive VR experiences [30]. These advances have helped to improve the user's sense of presence and interaction in the virtual environment.

In the mid-2000s, immersive VR platforms such as CAVE (Cave Automatic Virtual Environment) systems emerged, providing users with a room-sized immersive experience [21]. These systems are particularly popular in academic and industrial research and are used for tasks ranging from data visualization to architectural architecture. The CAVE system is an excellent example of these qualities, providing an immersive, high-resolution display that significantly enhances the user's sense of presence. The technology achieves this by creating a multi-screen environment that surrounds the user, providing a more immersive experience than traditional head-mounted displays (HMDs) [68]

Unlike HMDs, which have the potential to restrict the field of view and cause disorientation, the expansive surrounding screens of the CAVE provide a panoramic field of view. This configuration not only enhances spatial awareness, but also facilitates the interaction of multiple users in a shared virtual environment, optimizing its suitability for collaborative tasks. Such systems have been shown to be particularly effective in applications that require detailed spatial understanding, including architectural visualization, complex data analysis, and training simulations, where a high degree of presence can enhance learning outcomes and facilitate the transfer of skills to real-world scenarios [46]. The immersive experience provided by CAVE systems can be further enhanced by integrating multimodal sensory feedback. Combining visual stimuli with auditory and haptic feedback has been shown to significantly improve user performance and reduce errors in virtual reality environments. This multimodal approach ensures that the user's sensory input is more closely aligned with real-world experiences, thereby deepening immersion and increasing the sense of presence.

In 2012, the launch of the Oculus Rift marked a turning point in VR history. Oculus,

Figure 2.3: The CAVE System Setup [82]

founded by Palmer Luckey, has launched VR into the consumer market with affordable, high-quality HMDs that offer a wide viewing range, low latency and high resolution displays [50]. The success of the Oculus Rift sparked a wave of innovation and led to the development of other popular VR headsets, such as the HTC Vive and PlayStation VR, which democratized access to immersive experiences.

Between 2015 and 2020, VR technology experienced rapid advances in hardware and software. The introduction of the 6DoF controller (Six Degrees of Freedom) allowed users to move freely and interact more naturally with the virtual environment [5]. In addition, the development of graphic rendering, such as real-time radiation tracking, has made the environment more realistic and visually stunning [78]. The integration of haptic feedback and spatial audio further enhances immersive experience, allowing users to feel and hear virtual worlds as real.

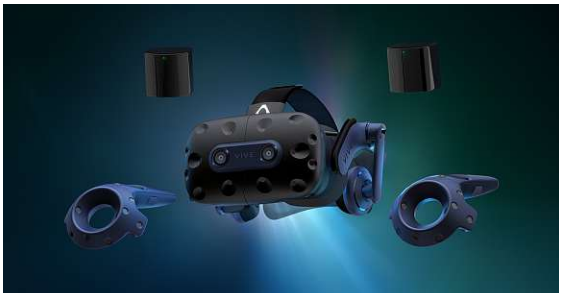
VR technology has made significant progress between 2020 and 2024, particularly in the field of hardware and software development. One of the most remarkable developments was the enhancement of the independent VR headsets, which no longer required connection to a powerful computer, making VR more accessible and user-friendly. Devices such as Oculus Quest 2 introduced higher resolution screens, improved refresh rates and advanced internal tracking, significantly improving user experience [80]. These improvements in hardware have been supplemented by innovations in rendering technologies, such as foveated rendering, which reduces computational load by adjusting the resolution based on the user's orientation, thus improving performance and immersion [44].

VR applications have experienced a significant growth in several areas beyond entertainment, including education, health care and remote collaboration. In the medical sector, VR has increasingly been used for therapeutic interventions, especially in the treatment of mental illnesses such as PTSD and anxiety disorders. Studies have shown that VR therapy can offer immersive exposure therapy, allowing patients to confront their fears in a controlled virtual environment, leading to significant improvements in clinical results [47].

The COVID-19 pandemic further accelerated the adoption of VR for remote collaboration, with organizations and educational institutions using VR platforms to create virtual meeting spaces that replicate closely real interactions and effectively address the limitations of traditional video conferences tools. During this period, the design of virtual classrooms in virtual environments became a decisive innovation to improve access and quality to remote education. This innovation enabled interactive and immersive learning experiences, offering students the opportunity to participate in educational content that traditional online platforms cannot [51]. The integration of artificial intelligence into these VR environments further enhanced the interaction and adaptability of virtual scenarios, expanding the scope and effectiveness of VR applications in various sectors. Major players in the industry include Facebook (Meta), which acquired Oculus and has invested heavily in the development of VR, HTC, known for its Vive headsets, and Sony with its PlayStation VR. In addition, companies such as Valve, Samsung, and Microsoft are making significant contributions to the VR ecosystem [36]. Market trends show a continuous expansion of VR applications that focus on improving user experience through higher resolution displays, better ergonomics, and more intuitive interactions. The integration of augmented reality and mixed reality technologies is expected to stimulate innovation and lead to a seamless and immersive experience.

The release of the HTC Vive Pro 2 in 2021 marked a new benchmark in VR with its 5K resolution display, 120-degree field of view, and 120Hz refresh rate, offering one of the most immersive experiences available to consumers [38]. Similarly, Apple's introduction of the Vision Pro in 2023 represented a major leap in mixed reality, combining VR and AR capabilities in a sleek, all-in-one headset. The Vision Pro features advanced eye-tracking, spatial audio, and the ability to interact seamlessly with digital content in the real world, setting new standards for immersive technology [7]. Beyond hardware, the integration of artificial intelligence and machine learning within VR environments has significantly enhanced user interactivity and content generation, making virtual experiences more dynamic and responsive. These advancements underscore the rapid evolution of VR technology, positioning it as a crucial component of future digital experiences across various industries.

In summary, the current state of VR technology reflects a mature and rapidly evolving field. With ongoing advancements in hardware and software, VR is set to play an increasingly integral role across diverse industries, offering transformative opportunities for immersive and interactive experiences.



(a) HTC Vive Pro 2 kit [73]

(b) Apple Vision Pro [8]

Figure 2.4: Modern VR HMDs

2.3 Key factors for evaluation

The efficacy of virtual reality as an immersive technology is dependent upon a number of critical factors that, when considered collectively, serve to enhance the user experience. These key factors include presence, immersion, motion sickness, and emotions. Understanding and optimizing these elements is essential for creating compelling VR environments.

2.3.1 Presence

Presence is a fundamental aspect of VR and is often referred to as the "sense of being there" [28]. This is a psychological state where users feel like they are really in the virtual environment rather than in their physical environment. This feeling of presence is important for the effectiveness of VR experiences because it directly influences user engagement and satisfaction. Several factors contribute to the presence of VR. For example, spatial audio plays an important role in providing auditory signals that align with the visual environment, thus increasing the realism of the experience [29]. Haptic feedback, which includes tactile sensations transmitted through devices such as haptic gloves and vests, also strengthens the presence by allowing users to feel interactions within the virtual world. In addition, high-resolution displays and accurate movement tracking are crucial to minimizing visual and latency issues and ensure that user actions are accurately reflected in the VR environment. Recent research has further explored the relationship between sensory cues and presence in VR. The study by Cooper et al. [20] demonstrated that the integration of substitute multisensory feedback, such as auditory and tactile cues, can significantly enhance both task performance and the sense of presence in VR environments. The findings suggest that even when sensory cues are not fully realistic, their presence can still improve users' immersive experience by providing additional information that enhances interaction and involvement. This implies that the strategic use of sensory feedback, even at the expense of some fidelity, can lead to higher engagement and a stronger sense of presence, particularly in tasks requiring high levels of interaction within the virtual environment.

2.3.2 Immersion

The term "immersion" is used to describe the extent to which a virtual reality (VR) system can engage the user's senses, creating the perception of a real environment. Unlike the presence, which is a psychological state, immersion is more about the objective properties of the VR system itself [83]. It refers to the extent to which a VR system can envelop the user's senses, creating a convincing and engaging virtual environment. Immersion is primarily concerned with the objective properties of the VR system, such as display quality, field of view, and interactivity [63]. Achieving high levels of immersion involves the use of stereoscopic 3D displays, which simulate depth perception, and head-mounted displays (HMDs) that provide a wide field of view (FOV), enhancing the sense of being surrounded by the virtual environment. These technical aspects are crucial as they allow users to feel more "inside" the virtual world, thus increasing the realism and overall experience [57].

In addition, interactivity plays a vital role in enhancing immersion. The ability for users to interact naturally and intuitively with the virtual environment through advanced motion tracking systems and adaptive VR controllers is essential. These systems track the user's movements and translate them into the virtual space in real-time, ensuring that the virtual experience responds accurately to the user's actions. This level of responsiveness and interactivity makes the experience more immersive, as users can manipulate and explore the virtual world as they would in the real world [57].

Recent studies have also highlighted the importance of multisensory feedback in enhancing immersion. For instance, Shaw et al. [66] evaluated different forms of sensory feedback, including auditory, physical resistance, and wind feedback, in an immersive exergame environment. Their findings demonstrated that all three types of feedback increased the level of immersion, with auditory feedback being particularly effective in enhancing the user experience. The study also found that combining multiple forms of feedback, rather than relying on a single type, produced the most immersive experiences. This research underscores the significance of integrating diverse sensory inputs to create a more holistic and engaging virtual environment.

2.3.3 Motion sickness

Motion sickness remains one of the major challenges in VR. It is caused by sensory mismatches between visual inputs from VR headsets and vestibular systems that control balance and spatial orientation [84]. This sensory mismatch can lead to symptoms such as nausea, dizziness, and headaches. One crucial factor is optimizing frame rates, as low or variable frame rates can exacerbate the discomfort experienced by users. Ensuring a consistent and high frame rate helps to maintain a smooth and continuous visual experience, which is critical in reducing the occurrence of motion sickness. Additionally, the type of virtual environment and the level of user interaction can also influence the severity of motion sickness. For instance, environments with rapid movements or poor synchronization between head movements and visual feedback can significantly increase the likelihood of discomfort [17]. Ensuring that the frame speed is stable and high, reducing latency, and making the virtual environment more comfortable to navigate are essential. In addition, movement algorithms that simulate natural movements, such as teleportation instead of continuous movements, can help alleviate symptoms [4]. Providing users with control over their movements and the integration of rest frames (static scenes) can also reduce the incidence of motion sickness.

2.3.4 Emotions

Emotions play a crucial role in VR experiences and have a significant impact on the user's engagement and overall effectiveness of the virtual environment. VR has a unique ability to stimulate strong emotional reactions due to its immersive nature [58]. For example, VR can create a sense of fear in horror games [49] or facilitate empathy in simulations that seek to raise awareness of social issues. Emotions are stimulated in VR through various mechanisms. Narrative content can create emotional connections by involving users in compelling stories. Environmental design, including visual aesthetics and ambient sounds, also contributes to the emotional tone of the experience. Recent research by Riches et al. [62] supports this view, highlighting how VR can effectively be used for relaxation and stress reduction among people with mental health conditions. Their systematic review indicates that VR experiences designed to evoke specific emotional responses can significantly enhance therapeutic outcomes by providing a controlled environment that mimics real-life triggers. Understanding the emotional impact of VR is crucial to designing experiences that are not only exciting but meaningful and memorable. According to recent research, the sense of presence in a VR environment is closely tied to the emotional responses users experience. This connection is particularly evident in scenarios designed to provoke anxiety or fear, where the realism of the virtual environment can trigger intense emotional reactions, similar to those experienced in real-life situations [25].

In summary, the main elements of VR – presence, immersion, motion sickness, and emotions – are interdependent elements that collectively shape user experiences. For the authors research these key factors will play a central role. From the initial design of the application to the subsequent evaluation, these factors will prove to be of critical importance.

2.4 Sensory feedback

Sensory feedback is a critical component of Virtual Reality that significantly enhances the immersive experience by engaging multiple senses. It does not only improve realism but also increases user engagement and satisfaction. This section explores the various forms of sensory feedback in VR, including visual, auditory, tactile, and other sensory modalities.

2.4.1 Visual

Visual feedback is the cornerstone of VR, mainly dictated by the way users perceive the virtual environment. Current visual feedback techniques include stereoscopic 3D and high-resolution displays. Stereoscopic 3D creates depth perception by presenting slightly different images to each eye, imitating the way human vision works [9]. This technology is crucial to creating realistic and immersive VR experiences. High-resolution screens with resolutions often over 4K provide clear and detailed images that increase the sense of presence. Field of View (FOV) is another important factor; more extensive FOVs extend peripheral vision and make the virtual world more inclusive and natural[40]. High-quality visual feedback can make virtual environments more convincing and engaging, facilitating deeper immersion. On the other hand, poor visual quality can destroy the feeling of existence and cause discomfort and disinterest. Therefore, continuous advances in display technology and rendering technologies are essential for the evolution of VR.

2.4.2 Auditory

Auditory feedback is a key element that significantly enhances immersion in virtual reality. Advanced 3D audio technologies, such as binaural audio, play a crucial role in creating a realistic and immersive sound experience. Binaural audio works by simulating how sound waves interact with the human ear, creating a three-dimensional soundscape that adjusts with the user's head movements. This technique is particularly effective in providing accurate spatial cues, thereby enhancing the sense of presence within the virtual environment [10]. Broderick et al. [12] emphasize the importance of spatial audio in modern games and virtual environments, highlighting how precise audio cues can significantly improve user navigation and interaction within these spaces. The study demonstrates that spatial audio not only enhances immersion but also provides critical information that aids in orientation and environmental awareness, making the virtual experience more engaging and realistic.

Binaural audio is a method of recording and reproducing sound that captures the way humans naturally perceive audio in three dimensions. It simulates the natural listening experience by using two microphones placed at the approximate positions of the human ears. This technology takes into account the way sound waves interact with the human head, ears and torso, creating a realistic spatial audio experience when reproduced through headphones. The basic principle of binaural audio is the concept of interaural time differences (ITD) and level differences (ILD). ITD refers to the slight difference in the time it takes a sound to reach each ear, which helps the brain determine the direction of the sound source. ILD is the difference in the sound pressure level reaching each ear, which also helps to localize the sound. Together, these cues allow the brain to determine the exact location of a sound source in the three-dimensional space around the listener [**?**].

In addition, the Head-Related Transfer Function (HRTF) plays a critical role in binaural audio. HRTF is a response that characterizes how an ear receives sound from a point

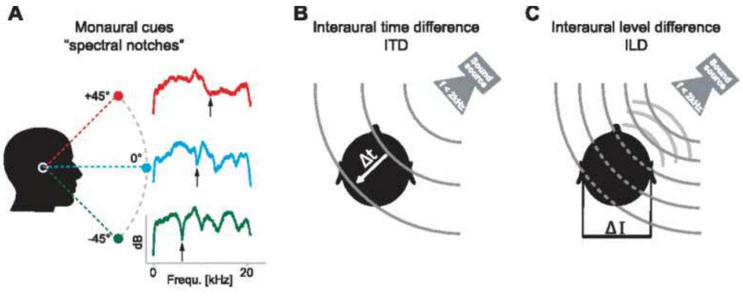


Figure 2.5: Explanation of binaural audio techniques [31]

in space, taking into account factors such as the shape of the ear (pinna), head and body. When applied to a sound signal, HRTF filters it in a way that mimics how sound would be altered by human anatomy, allowing precise simulation of sound coming from any direction [61, 77]. The author thinks that binaural audio is essential for creating immersive VR experiences as it greatly enhances the sense of presence and spatial awareness in a virtual environment. It allows users to perceive sounds as if they were happening in the real world around them, making the VR experience more realistic and engaging. This technique is often used in conjunction with visual and haptic feedback to create a fully immersive environment. More recent research by Kern and Ellermeier [45] demonstrates that audio elements, such as soundscapes and movement-triggered step sounds, play a crucial role in maintaining a high level of presence in VR environments. Their study found that such auditory cues not only contribute to the spatial realism but also enhance the immersive experience by aligning sound feedback with user actions. Recent developments in binaural audio generation, particularly those using mono audio sources, have further expanded its applicability. The process of converting mono audio to binaural audio by utilizing depth and visual cues from the scene has shown promising results in delivering a highly immersive auditory experience without the need for complex recording setups. This method not only recreates the spatial properties of sound sources but also enhances realism by incorporating depth information, which is critical for accurate sound localization in VR environments [56]. Implementing such dynamic and responsive auditory environments in VR can significantly elevate user participation by providing contextual audio signals that enrich the overall sensory experience.

2.4.3 Tactile feedback

Tactile feedback, or haptic feedback, refers to providing physical sensations that correspond to interactions in the virtual environment. State-of-the-art haptic technology includes haptic gloves and vests that allow users to feel textures, shapes, and resistance, thus enabling more natural and intuitive interaction with virtual objects. Devices like the Manus VR and HaptX gloves use various mechanisms to simulate tactile sensations, such as force feedback and vibrations. Haptic vests, such as Teslasuits, provide full-body feedback, allowing users to feel effects like temperature changes and other physical sensations.

These vests use a series of actuators distributed throughout the body to provide precise tactile feedback, enhancing the feeling of presence and immersion. Recent studies have highlighted the importance of tactile feedback in VR, particularly in applications such as surgical training and delicate operations. For example, research by Cheng et al. [18] demonstrated that vibrotactile feedback could significantly improve task performance in virtual environments, particularly in delicate tasks requiring precision and control. The study found that adding vibrotactile feedback to visual and audio cues helped users complete tasks more quickly, although it also led to increased pressure on manipulated objects, indicating a potential trade-off between speed and delicate control. Further advancements in haptic technology have explored the use of electro-tactile feedback as an alternative to traditional mechanical feedback systems. Pamungkas and Ward [55] developed an electro-tactile feedback system that delivers tactile sensations via mild electric currents applied to the skin, offering a more compact and less cumbersome solution compared to mechanical actuators. This system has been shown to enhance both immersion and interactivity in VR environments by providing a diverse range of tactile sensations without the bulkiness of traditional haptic devices. In medical training, the role of haptic feedback has been extensively studied, particularly in laparoscopic surgery simulators. A study by Våpenstad et al. [75] revealed that while haptic feedback is considered crucial for simulating realistic tissue interactions, the implementation of such feedback often introduces additional friction, which can detract from the realism of the experience. Despite this, the emulation of haptic feedback remains a vital component in training surgeons, as it helps in developing the necessary skills for real-world operations.

2.4.4 Other

While visual, auditory, and tactile feedback are the main sensory modes of VR, other forms of sensory feedback, such as olfactory and gustatory, are attracting attention. Olfactory feedback involves using smells to improve immersion. The study by Serrano et al. [65] explored the use of olfactory stimuli, specifically lavender scent, in enhancing virtual reality experiences. While the addition of smell did not significantly improve relaxation or presence compared to visual and auditory stimuli alone, it showed potential to enhance immersion. Participants exposed to the scent reported a trend towards greater relaxation, suggesting that olfactory cues can enrich the sensory experience and emotional engagement in VR when used alongside other stimuli. Generally, although less common, gustatory feedback involves simulating taste sensations. While in the experimental phase, researchers are exploring ways to incorporate taste into VR, potentially expanding its applications in areas such as cooking training and virtual dining experiences [34].

In conclusion, sensory feedback in VR is crucial to creating immersive and stimulating experiences. This thesis will focus on the evaluation of auditory and tactile feedback. Since there are many studies available regarding the visual senses, while other sensory feedback systems are not available and harder too evaluate. The clear focus lies on 3D audio technology and tactile feedback through vibration.

2.5 Design principles

Designing compelling and immersive virtual reality experiences requires an in-depth understanding of design principles tailored to the unique characteristics of virtual environments. Key principles for immersive design emphasize realism, interactivity, consistency, and feedback. Realistic rendering, including accurate object modeling, lighting, and high-quality textures, is essential for creating believable environments that enhance immersion. The concept of immersion is further strengthened when these elements are combined with responsive and intuitive interactions, allowing users to feel truly part of the virtual world. This can be seen in the "Claustrophobia Game," which uses realistic VR environments to treat anxiety disorders by simulating enclosed spaces like elevators and MRI machines, providing a safe yet convincing experience for users [24]. Consistency in visual and auditory styles throughout the VR experience is crucial for maintaining immersion. Inconsistencies can disrupt the sense of presence and remind users of the artificial nature of the environment. Immediate and appropriate feedback—both visual and haptic—reinforces the sense of being in a responsive and interactive world, making the virtual experience more immersive and engaging [92]. User-centered design (UCD) is another critical aspect, placing the user's needs at the center of the design process. This involves creating comfortable and accessible experiences, which is particularly important in VR to prevent discomfort such as motion sickness. For example, the design of VR systems must account for ergonomics by optimizing the weight and balance of headsets and ensuring that controllers are intuitive and comfortable to use. Additionally, providing adjustable settings for text sizes, control schemes, and options to minimize motion sickness ensures that VR experiences are inclusive and accessible to a broader audience [24]. Intuitive navigation is also a key factor in user-centered design, helping users move through the virtual environment without confusion or frustration. This involves using natural locomotion techniques like teleportation or room-scale movement, complemented by clear visual cues for interaction points. In VR environments, effective navigation not only enhances usability but also contributes to the overall enjoyment of the experience. Designing virtual environments involves careful consideration of architectural principles and environmental storytelling. Spatial layout should facilitate easy navigation, with logical layouts and clear landmarks helping users orient themselves naturally. Proper scaling of objects and environments is vital to maintaining realism; disproportionate elements can break immersion and affect the user's perception of space. Environmental factors like lighting, sound, and atmospheric effects play a significant role in setting the mood and enhancing the narrative, creating environments that evoke specific emotions and enhance the overall experience. Wagener et al. [76] emphasize the importance of designing VR environments that support emotion regulation by integrating intuitive navigation with thoughtfully designed spaces. Their research suggests that by considering emotional impact during the design process, VR applications can better facilitate users' emotional well-being, making the environment both engaging and therapeutic.

Case studies of effective VR design provide valuable insights into successful approaches. For instance, "Job Simulator" by Owlchemy Labs excels in interactivity and humor, creating an engaging and intuitive environment with a consistent, exaggerated, cartoonish design that enhances the immersive experience [74]. “Google Earth VR” is another great example, where the user gets immersed in a another world, in this case a representation of the real world. The intuitive navigation makes it easy to navigate through a 3D version of the earth, which allows the user to immerse themselves in any specific location. While the interaction is limited to navigating, is is interesting enough to keep users immersed for a long time period. [85]. “The Climb” by Crytek leverages realistic graphics, precise motion tracking, and immersive sound design to create a thrilling experience, with careful consideration of physical interaction and feedback enhancing the sense of presence and adventure [35].

In summary, effective VR design requires a balance of realism, interactivity, and user-centered considerations. By focusing on ergonomic comfort, accessibility, and thoughtful environmental design, creators can develop VR experiences that are immersive, engaging, and inclusive. These principles, coupled with lessons from successful applications, provide a roadmap for creating compelling VR environments that resonate with users.

2.6 Related work

Numerous projects and studies have explored the critical role of sensory feedback in enhancing immersion and presence in virtual reality (VR). This section reviews key contributions to the field, focusing on how they address multisensory feedback and the challenges of achieving high levels of user engagement through tactile and auditory stimuli.

The work of Slater and Wilbur [68] laid the groundwork for understanding the concept of presence in VR environments, emphasizing the importance of consistent and realistic sensory input to foster a deep sense of ’being there’ in virtual spaces. Their study showed that even subtle inconsistencies between sensory modalities, such as visual and auditory stimuli, can disrupt presence, highlighting the need for seamless integration of sensory feedback. This principle provides an important foundation for their research, particularly in the context of ensuring that both binaural audio and haptic feedback are tightly synchronized to create a cohesive virtual experience. More recently, McMahan et al. [52] investigated the impact of high-fidelity visual and auditory feedback on user immersion, showing that higher quality sensory input significantly enhances the sense of presence. While their study focused primarily on visual and auditory cues, it did not explore the potential synergy between these and other sensory modalities, such as haptics. This highlights a gap in the literature where multimodal integration, particularly between binaural audio and haptic feedback, has not been fully explored. Her research aims to address this gap by investigating how the combination of these two sensory inputs can enhance user immersion and engagement in VR environments. The 2015 Oculus Spatial Audio Research Study further underscores the importance of accurate 3D sound in VR. The study found that spatial audio significantly improves users’ ability to orient and navigate in virtual environments by providing critical spatial cues [64]. However, the study focused primarily on auditory feedback in isolation, without considering how tactile feedback could complement the auditory experience to create a more immersive environment. This gap suggests that further research is needed to evaluate the combined effect of binaural audio and haptic feedback, which your thesis will investigate in the context of user engagement and presence. The Virtuix Omni project explored the role of whole-body motion tracking in enhancing physical participation and presence in VR. Their findings suggest that allowing users to walk and move naturally in virtual environments enhances immersion. While this study focuses on kinesthetic feedback, it highlights the broader importance of integrating multiple sensory modalities to enhance the VR experience. The mentioned research will extend this concept by specifically evaluating the interplay between binaural audio and haptic feedback, with the aim of understanding how the integration of auditory and haptic cues influences user immersion without the need for full-body movement systems [72].

Similarly, the "Claustrophobia Game" project investigated the effects of environmental sensory stimulation on users with anxiety disorders using accurate tactile and auditory feedback to create a calming, controlled environment. The study demonstrated that controlled exposure to simulated confined spaces, enhanced by accurate tactile and auditory feedback, could help reduce anxiety symptoms, showcasing the therapeutic potential of VR environments when designed with sensory stimulation in mind [60]. Another project, "The Climb" by Crytek, focused on the use of realistic graphical and auditory stimuli combined with precise motion tracking to create an intense, physically engaging experience. The study found that users experienced a heightened sense of presence and physical engagement, indicating that multisensory feedback is key to creating compelling and immersive VR experiences [2].

The Virtual Jumpcube, developed by Eidenberger in 2015, offers a case study of how integrating multiple sensory modalities can enhance immersion and user experience in virtual reality environments. This system combines audiovisual feedback with olfactory and haptic stimuli, allowing users to engage in a fully immersive jumping and flying experience. Unlike traditional VR systems, the Virtual Jumpcube employs complex mechanical setups to simulate physical sensations, such as wind, force, and suspension, which are carefully synchronized with the virtual environment. Eidenberger's primary goal was to investigate how the addition of olfactory and tactile stimuli can heighten immersion, excitement, and minimize motion sickness during VR experiences. The results of his experiments demonstrated that participants reported significantly higher levels of immersion when haptic and olfactory feedback were included, especially when these stimuli were carefully aligned with visual and auditory cues. For example, sensations such as wind or water spray, delivered during virtual skydiving, were found to increase engagement by providing realistic tactile feedback. Participants overwhelmingly responded positively to these stimuli, citing them as crucial to the overall experience [27].

The study by Bruun-Pedersen et al. [15] investigated the influence of multimodal feedback, particularly auditory and haptic stimuli, on perceived exertion in a virtual reality exercise context. The findings offer valuable insights for the design of immersive virtual environments. The study involved participants utilizing a stationary exercise bike within a simplified desert virtual reality environment, with variations in auditory and haptic feedback to simulate different exertion levels. Contrary to the hypothesis that such feedback would significantly alter perceived exertion, the results indicated no substantial differences across the conditions tested. However, the qualitative responses indicated that some participants perceived alterations in mechanical resistance and found the experience inconsistent with their real-world expectations, primarily due to the absence of gravity simulation in the virtual environment. This outcome emphasizes the necessity of aligning virtual sensory feedback with real-world physics to enhance user immersion and efficacy in VR applications, particularly in the context of exercise and rehabilitation. The study highlights the importance of further research on multimodal feedback to elucidate its role in shaping user experience in VR, in line with ongoing efforts to investigate under-researched areas of sensory feedback and their potential to influence engagement and immersion in virtual environments [15].

Figure 2.6: The Setup used by Bruun-Pedersen [14]

These studies and projects collectively highlight the critical role of multisensory feedback in achieving immersive VR experiences, demonstrating the importance of integrating visual, auditory, and tactile stimuli to create more convincing and engaging virtual environments. However, the combination of binaural audio and tactile feedback in particular has hardly been researched, which contributes to the ambition to investigate it further in this thesis. The research by Bruun-Pedersen et al. provides a good starting point, highlighting both the possibilities and limitations of combining audio and tactile feedback. Their study will serve as a framework for comparing results, as it uses a similar system (2.6) to this study. In the following chapter the design of the study as well as the requirements and the design of the VR experience will be presented.

CHAPTER 3

Design and concept

The following describes the conception and design of the VR system. The system is derived from the project idea "Phantastic Sound Experience" by Professor Dr. Horst Eidenberger [1]. The requirements that form the basis of the design are described first, followed by the research and concept that led to the implementation. To effectively evaluate the impact of auditory and tactile feedback on immersion and presence in virtual reality, the system design and implementation must meet several key requirements. These requirements ensure that the VR environment not only supports the necessary sensory modalities but also provides a stable and reliable platform for comprehensive testing and evaluation.

3.1 Requirements

3.1.1 Uniformity of participant experience

The VR experience should be designed to ensure that each participant experiences an equivalent sequence of events, interactions, and sensory stimuli. This uniformity is critical for generating comparable evaluation data across all participants and directly supports the research objective by ensuring that any variation in participant responses can be attributed to the sensory feedback being tested, rather than discrepancies in their individual VR experiences. As Bowman et al. [11] argue, consistency in the VR environment helps to control the variables that might otherwise impact user experience and interaction. Similarly, Slater and Wilbur [68] emphasize that a controlled and consistent virtual environment is essential for studying presence and immersion, as it allows researchers to isolate the effects of specific sensory inputs. By maintaining consistency in the virtual experience, the variability that could arise from different participant interactions is minimized. This consistency is particularly important when evaluating the effects of auditory and tactile feedback on immersion and presence, as it ensures that differences in participants' responses can be attributed to the sensory modalities being tested, rather than to variations in the VR experience itself. Thus, the principle of uniformity directly supports the reliability and validity of experimental results, allowing researchers to draw more accurate conclusions about the impact of specific sensory inputs on user experience.

3.1.2 Balanced and immersive virtual environment

The virtual environment should strike a careful balance between being engaging enough to promote immersion and neutral enough not to overshadow other sensory inputs. This balanced design supports the research objective of investigating how auditory and tactile feedback influence immersion by ensuring that sensory inputs are the primary focus. The design should be compelling enough to maintain a high level of presence but subtle enough to allow auditory and haptic feedback to be the primary focus of evaluation. Potter et al. [59] emphasize that achieving this balance is crucial because both visual and audio rendering play significant roles in shaping user immersion. Their study shows that while high-resolution visuals enhance presence, spatial audio—especially when augmented with room acoustics—can have a similarly profound impact. This finding highlights the need for a nuanced approach to designing VR environments that do not dominate but rather complement sensory stimuli being tested. This balance is essential to ensure that the sensory stimuli being tested are the dominant factors influencing participant immersion and presence, thereby supporting the overall research objectives. In addition, the environment should include adjustable elements such as lighting and sound levels that can be tailored to meet the specific needs of different experimental conditions, further aligning with the modular design of the system.

3.1.3 Integration of sensory feedback

The VR system should seamlessly integrate hardware and software components to support visual, auditory, and tactile feedback to ensure a cohesive and immersive experience. Effective VR design, as suggested by Jerald [43], requires the tight integration of these elements to enhance user immersion and presence. This includes the development of a customizable virtual environment capable of controlling and synchronizing sensory output. The hardware configuration must include spatial audio systems and haptic devices, both of which play a critical role in simulating real-world sensory experiences. Synchronization of these components is essential to deliver auditory, tactile and visual stimuli in harmony to create a seamless sensory environment. According to Cummings and Bailenson [22] the synchronization of sensory modalities is fundamental to improving the overall sense of presence and ensuring that the virtual experience feels natural and convincing. Sensory feedback needs to be perceived as an integral part of the virtual environment, rather than a separate layer, so the interplay between these stimuli is key to achieving high levels of immersion. Han et al. [33] further emphasis the importance of multisensory feedback integration, highlighting systems such as 'Haptic Around' that combine tactile feedback mechanisms to simulate environmental factors such as wind, heat and humidity.

Their findings show that a range of tactile sensations enhances realism by making sensory feedback feel connected and authentic. Minimizing latency or mismatch between these inputs is critical to maintaining the illusion of reality and ensuring the immersive quality of the VR experience.

In addition, the system should allow the intensity and timing of sensory feedback to be adjusted to suit specific experimental conditions or participant preferences. This flexibility enhances the adaptability of the system and supports broader research goals by enabling tailored sensory experiences in different experimental setups.

3.1.4 Participant centered design and accessibility

Given that many users may be new to virtual reality, the system must be designed with a strong emphasis on participant comfort and accessibility. This requirement is closely related to the balanced virtual environment, as an overwhelming or overly complex environment could detract from the user experience. The system should minimize potential overwhelm by providing an intuitive interface and gradually introducing participants to the VR environment. Accessibility features, such as customizable haptic feedback and adjustable control schemes, must be included to accommodate users with varying physical abilities. Additionally, the ergonomic design of the system is essential to prevent physical fatigue and allow participants to remain in the virtual environment for extended periods of time without discomfort. Yao and Kim [91] highlight that maintaining a high level of presence and engagement in VR environments is significantly influenced by physical comfort and ease of interaction. Their research shows that a well-designed, user-friendly VR setup not only enhances immersion but also encourages physical activity, which can further elevate the sense of presence. By ensuring that the system is user-friendly and accessible, the likelihood of distraction due to physical or cognitive strain is minimized, which in turn supports the overall goal of maintaining a consistent and immersive experience for all participants.

3.1.5 Optimised test duration and engagement

User testing sessions should be designed to optimize participant engagement and data collection. This requirement is related to participant-centered design, as the duration of the test has a direct impact on the user's comfort and willingness to engage with the VR system. The duration of the test should be long enough to allow participants to fully engage with the VR experience and provide meaningful feedback, yet short enough to avoid boredom or fatigue. The experience should also be designed to progressively introduce participants to the VR environment and sensory feedback mechanisms, allowing them to adapt before more complex interactions are required. This progressive engagement ensures that participants are neither overwhelmed nor under-stimulated, maintaining a high level of immersion throughout the session. Incorporating an adaptive testing mechanism that adjusts session length based on participant engagement levels can further enhance the quality of data collected and ensure that the experience remains both engaging and informative [16].

3.1.6 Evaluation tools

To assess the effectiveness of the sensory feedback, the evaluation with participants should be possible directly after testing and include both quantitative and qualitative measures. Quantitative assessments should employ standardized scales like the Igroup Presence Questionnaire and the Immersion Tendencies Questionnaire to objectively measure presence and immersion. Additionally, the system should facilitate the collection of qualitative feedback through open-ended questions that allow users to describe their experiences and suggest improvements. Kim et al. [46] demonstrated the importance of using multimodal sensory feedback, such as auditory, visual, and haptic cues, in enhancing user performance and presence in VR environments. Their study found that the effectiveness of these sensory modalities could be better understood through comprehensive evaluation methods that combine both quantitative metrics and qualitative insights. These tools are essential for gathering meaningful data that will inform the development of more immersive VR systems by highlighting how different sensory inputs contribute to the overall user experience.

3.2 Design approach

Having identified the key requirements for enhanced immersion in virtual reality through multisensory integration, this section outlines the chosen design approach for the system and builds a bridge to the employed methodology.

3.2.1 Experience design

The design approach focuses on creating a virtual world experience that prioritizes objectivity instead of interactivity, as outlined in requirement . Therefore it was decided to design a passive virtual environment, instead of developing a game, which often involves complex interactivity and tasks that can vary significantly between users. In this environment, participants take on the role of observers or 'passive users' rather than active players. This choice ensures that all participants share a similar experience, allowing them to focus on the sensory aspects of the environment without being distracted by game play mechanics or objectives.

3.2.2 Physical device integration

The challenge of connecting the virtual and real worlds through tactile feedback was a major focus of this design approach. While many VR controllers on the market provide some form of tactile feedback, the intensity and realism of these sensations are often limited. There are several commercially available solutions to enhance tactile feedback, such as haptic gloves and suits, which provide a more immersive experience by simulating the sense of touch. Examples include the TeslaSuit, which provides full-body haptic feedback, and the HaptX gloves, which provide detailed tactile sensations through microfluidic technology. However, these solutions are typically expensive and may not be accessible to all users or practical for large-scale implementation in research or consumer settings. Given these limitations, it was decided to design and build a custom physical device specifically tailored to the needs of this virtual experience. The idea was to create a physical component that could be directly represented in the virtual world, allowing real-world vibrations and tactile sensations to be seamlessly translated into the VR environment. This approach not only reduces costs, but also allows for a more controlled and targeted application of haptic feedback, enhancing the overall immersive experience. This also enables the possibility of incorporating accessibility in the design, supporting the requirements of 3.1.4. The design process involved brainstorming and sketching different concepts for the physical device. The aim was to develop a solution that could effectively simulate the sensation of touch in a way that was both realistic and synchronized with the virtual environment. Several design iterations were considered, each exploring different methods of integrating the physical and virtual components. The chosen design focuses on a device that can provide adjustable levels of vibration and pressure, allowing for a range of tactile experiences that can be fine-tuned to suit specific scenarios within the virtual world. The device is intended to be simple yet effective, using readily available materials and components to keep costs down while maximizing the impact on the user experience. The design also takes into account the ergonomics and comfort of the user, ensuring that the device can be used for long periods of time without causing discomfort or fatigue.

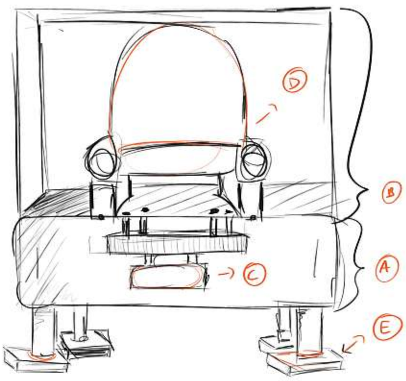


Figure 3.1: Sketch, first draft of the physical construction

The implementation details of the device, including its construction and integration into the virtual environment, are described in more detail in the following section 4.3.1. This section will cover the technical aspects of the device, including the specific materials and components used, as well as the methods for synchronizing the physical and virtual worlds to achieve the desired level of immersion. Through this design approach, the system aims to provide a more immersive and objective virtual reality experience, enhancing the user's sense of presence and engagement in the virtual world.

3.2.3 Multisensory feedback synchronization

The main idea of the sensory feedback was to link events in the virtual world with the corresponding senses. This ensures a synchronized line of events for the sensory feedback. To ensure a seamless experience for the player in virtual reality, it is essential that the audio and vibration correspond to the same location. In order to achieve this synchronization, the vibrations should be linked to the audio. The sequence of sensory feedback is be represented in the following flowchart:

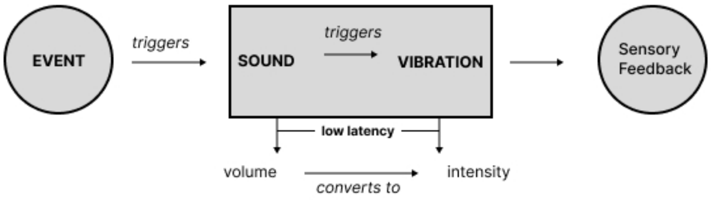


Figure 3.2: Illustration of synchronized feedback loop

So the event in the virtual world determines the volume of the audio, and the volume of the audio determines the strength of the oscillation. This system ensures that all sensory modalities are correctly aligned, providing a smooth and immersive user experience. Synchronizing these inputs can present technical challenges, particularly in minimizing latency between audio and tactile feedback. Drawing from research on the importance of synchronized sensory feedback as outlined in 3.1.3, the system leverages advanced processing techniques to minimize delay. For example, when an object hits the virtual glass cube, the corresponding sound and tactile vibrations are delivered almost instantaneously. How this can be achieved will be shown later in the section 4.3.3 of the implementation chapter.

3.2.4 Test design

The test structure was designed to be consistent and repeatable, ensuring a uniform experience for each participant. Users first received an introduction to the environment to help them acclimate to the virtual world. During the test they observe objects interacting with their environment from within the glass cube, experiencing synchronized audio and tactile feedback. The test lasts five minutes each, with a sequence of events designed to gradually increase the complexity and intensity of the stimuli. The controlled, non-interactive environment ensures that each participant has a similar experience, supporting the requirement for uniformity. This is necessary to provide a clear and consistent test procedure, ensuring robust data collection across multiple participants. The test design supports the aim of the study to isolate the effects of multisensory feedback on immersion.

3.2.5 Evaluation plan

The evaluation of the sensory feedback system includes both qualitative and quantitative methods to ensure a thorough analysis of its effectiveness. Key metrics for evaluation include user reported immersion and presence inspired by standardized questionnaires such as the Igroup Presence Questionnaire and the Immersion Tendencies Questionnaire. Qualitative feedback was collected through open-ended questions, allowing participants to describe their experience and highlight any potential discrepancies between sensory modalities. A statistical analysis was be employed to identify the impact of sensory feedback on the level of immersion experienced by participants, thereby ensuring the accurate analysis of the data. This comprehensive evaluation plan provides a clear understanding of the system's ability to enhance presence and immersion through multisensory integration.

3.3 Conception of the VR experience

The objective of this "Phantastic Sound Experience" is to investigate the potential of combining auditory and tactile feedback to significantly enhance user immersion and presence in a virtual reality environment. This section presents the concept that was implemented and the design of the system in order to include sensory feedback. Moreover it displays how the design choices support the research objectives. The following will detail how the VR experience is designed to serve as a basis for the subsequent evaluation and analysis.

3.3.1 Game concept

In the virtual environment, the user is placed in a glass cube which is placed in the center of the room. This room, designed to respond dynamically to the accompanying music, gradually fills with a variety of objects. These objects move through the air and collide with the glass cube, producing sounds that trigger the vibration, synchronizing the physical vibrations with the virtual events. What differentiates this system from aforementioned projects is the decision to use a non-interactive, passive environment. Unlike traditional VR systems that rely on user actions and interactivity, this design focuses on providing a consistent sensory experience where all users observe and experience the same sequence of events. This not only ensures uniformity, but it also allows the study of sensory feedback in a controlled setting, free from the variability that interaction might introduce. The synchronization between auditory and tactile feedback is crucial to maintaining immersion, as it ensures that the sensory input matches the visual stimuli, creating a cohesive and believable experience. This approach directly supports the requirement for 3.1.3, where the interplay between sensory modalities must be seamless to avoid disrupting the user's sense of presence.

This non-interactive design marks a departure from research such as that of Bruun-Pedersen et al, where VR systems have been used to modulate physical effort through user interaction in a more active context. By concentrating on a passive, observational setting, the system identifies the impact of sensory feedback (sound, touch and sight) on user immersion, eliminating the potential for confounding variables introduced by user interaction. This approach provides a more controlled and comparable dataset across participants, emphasizing the sensory experience itself as the primary factor influencing immersion. In addition, the environment incorporates elements that respond to the audio cues, with the volume of the sound depending on the proximity of the user and the surrounding components. This dynamic interaction between the user and the environment is designed to maintain engagement and immersion without overwhelming the user, in line with the requirement for a balanced virtual environment as described in 3.1.2. By calibrating the complexity of the environment, the design ensures that it remains engaging without overshadowing the primary focus on auditory and tactile feedback. The interactive experience is characterized by an increasing level of animation within the space, with objects interacting more intensely with the glass cube as the musical accompaniment progresses. This results in a moment when the cube, with the user inside it, begins to float in space. This escalation is intended to create a compelling and dynamic experience that fully engages the user's senses, potentially creating a lasting sense of presence and immersion. This design strategy supports the requirement for optimized test duration and engagement from 3.1.5, ensuring that participants remain engaged throughout the experience, allowing for a thorough and meaningful evaluation of their responses to the sensory inputs. In addition, the dynamic behaviour of objects and sound cues further differentiates this system from existing research. Rather than relying solely on user interaction to drive immersion, our design uses the movement of objects and their corresponding sounds to maintain engagement. For example, when objects collide with the glass cube, the sounds produced are not only spatially accurate, but also trigger corresponding tactile feedback in real time, seamlessly and dynamically aligning auditory, visual and physical sensations. This synchronization ensures a high level of immersion, even in the absence of direct user interaction, and offers a different perspective on how virtual environments can maintain user engagement through sensory stimuli alone.

The decision to maintain a neutral yet engaging environment is also critical. The virtual world is kept simple yet realistic, with enough detail to create a strong sense of presence without overwhelming the user. This approach helps to ensure that the environment does not distract participants from the primary focus of sound and tactile feedback, and that their attention remains focused on the sensory elements being studied. This simplicity supports the uniformity mentioned in 3.1.1 as it minimizes the risk of external variables affecting the results, thus ensuring consistency across different users. Interactive elements are incorporated not only to maintain participant interest, but also to provide a comprehensive assessment of presence and immersion. By engaging users through these interactions, the design allows for a more robust assessment of how auditory and tactile feedback contribute to the overall VR experience. This is in line with the principle of user centered design as mentioned in 3.1.4, which emphasizes the importance of creating a system that is both accessible and engaging, allowing users to fully immerse themselves in the virtual environment without physical or cognitive strain.

Overall, this design approach ensures that the virtual world remains dynamic and engaging, while emphasizing the importance of audio and tactile feedback in creating a realistic and immersive VR experience. The combination of a neutral yet interesting environment, strategic environmental elements and interactive dynamics supports a comprehensive assessment of presence and immersion in virtual reality. By integrating these design choices with the core requirements, the system is able to provide valuable insights into the role of multisensory feedback in enhancing VR experiences.

3.3.2 Design of the environment

Figure 3.3: Front view Bofill's of La Muralla Roja [19]

The environment is designed as a floating virtual architectural structure in the sky inspired by Ricardo Bofill's works, especially La Muralla Roja (3.3). This structure offers a neutral but interesting environment that aligns with the principles of simplicity and realistic design as defined in 3.1.2. One of the first design sketches in blender is shown in 3.4. Within this architectural space, elements are strategically placed to ensure that the room does not appear empty and improve the spatial experience. At the center of this virtual environment is a concrete-based glass cube where participants sit. This central position helps to focus interaction and sensory experiences around the participant, strengthening their sense of presence in the virtual world. To create dynamic and engaging experiences, the virtual world includes various interactive elements. The room is gradually filled with 3D spheres that collide with the glass cube. These collisions produce sound and vibration, which are key to assessing participants' immersion and presence. This system allows constant interaction without requiring the participant to move around in the real world, thus maintaining a balance between engagement and practicality. As the number of spheres increases and interacts more frequently with the cube, they create a continuous and evolving sensory experience. Furthermore, sphere movement and related audio sources improve spatial audio awareness and contribute further to environmental immersive quality.

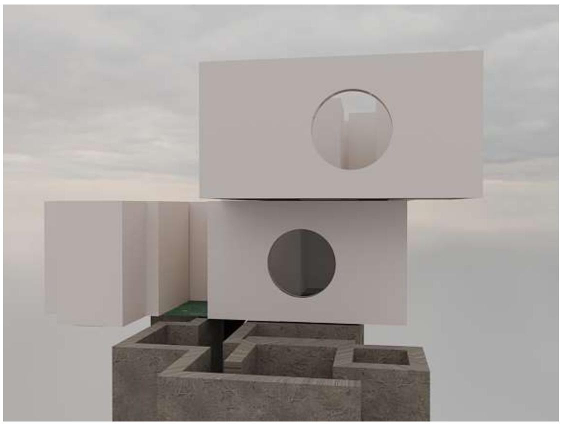


Figure 3.4: Explorative rendering of virtual world

3.3.3 Audio

As described in 2.4.2, audio plays a crucial role in enhancing realism and immersion to create an interactive virtual world. In reality, there is always a certain amount of background noise, and reproducing this in the virtual environment helps to create an atmosphere that feels alive and engaged. The soundscapes are designed to evoke the feeling of being in the sky and contribute to the overall feeling of being in another dimension or virtual world. This involves creating a soundscape that evokes the vastness and serenity of the sky. In addition, various sound effects need to be synchronized with interactions in the virtual world. For example, each collision between spheres and objects generates a sound based on the physical properties of the objects, ensuring that the audio feedback matches the visual and haptic experience. The placement of sound sources in the virtual world is critical to achieving realistic and immersive sound. Each sound must be placed and calibrated to match the visual elements and physical interactions in the environment. This realistic sound placement enhances the user's sense of space and presence. Multiple tests and adjustments ensure that the soundscape is harmoniously integrated into the virtual world. For example, as spheres move and collide in space, their associated sounds accurately reflect their position and movement, providing a coherent and immersive auditory experience. Implementing 3D audio in the VR environment requires advanced audio technologies to create a realistic soundscape. A spatializer is used to generate three-dimensional sound, allowing users to perceive the direction, distance and movement of sounds in virtual space. Binaural audio technology simulates how the human ear naturally hears sounds from different directions, enhancing immersion. Dedicated audio engines, such as Unity's, enable real-time processing and synchronization of audio signals with visual and tactile feedback. These tools ensure precise control of spatial audio effects, creating an immersive and realistic sound environment [41].

Comparing the authors approach to auditory feedback with Bruun-Pedersen et al.'s research, several similarities emerge. Both systems aim to synchronize auditory feedback with physical events in the virtual world. In their virtual exercise study, Bruun-Pedersen et al. used dynamic auditory feedback to reflect user effort, whereas in the "phantastic sound experience" sound is synchronized with environmental events such as object collisions. However, while the work focused on modulating auditory feedback to influence perceived physical exertion, the system uses sound to enhance the user's sense of immersion, allowing participants to focus on sensory stimuli and environmental interactions rather than physical performance [15]. This approach aligns with our research objective to explore how sensory feedback contributes to immersion by creating an environment where auditory feedback complements visual and tactile inputs to support a seamless sensory experience.

The combination of audio and tactile feedback is critical to creating a cohesive sensory experience. Just as spatial audio provides directional and distance cues, tactile feedback must be seamlessly integrated to reflect the physical sensations associated with these sounds. This link ensures that when users hear objects interacting in virtual space, such as collisions, they feel corresponding vibrations, adding a layer of physical realism to the auditory experience. The following section explores how tactile feedback, in combination with audio, plays a central role in creating a believable virtual world.

3.3.4 Tactile feedback

Tactile or haptic feedback enhances immersion in virtual reality by providing physical sensations that correspond to the user's interactions in the virtual world. This feedback bridges the gap between the virtual and physical experience, making virtual environments more believable and engaging. Several projects have integrated tactile feedback into VR, such as tactile gloves and vests that simulate touch and force. The HTC Vive controllers, for example, use vibration motors to give users tactile responses during interaction. These design principles ensure that tactile feedback matches the virtual interaction, enhancing realism and user engagement [67, 23].

For the "Phantastic Sound Experience", tactile feedback is implemented using vibration motors to simulate physical sensations. The buttkicker module, a key component, produces vibrations that simulate various interactions, such as the collision of virtual spheres with the glass cube. This hardware is critical to providing realistic tactile feedback that enhances the overall immersive experience. The synchronization of tactile feedback with virtual events is essential for immersion. For example, when virtual spheres collide with the glass cube, vibration motors are activated to provide tactile feedback corresponding to the impact. This synchronization ensures that physical sensations match virtual actions, enhancing realism and immersion. Some reference projects, such as Adelsberger's, have demonstrated the benefits of integrating tactile feedback to significantly improve user participation and presence. In the " Phantastic Sound Experience", virtual interactions are closely linked to vibration feedback, ensuring a consistent and immersive experience for participants [3]. Bruun-Pedersen et al.'s study also integrated tactile feedback, using vibration motors to simulate physical effort during a VR cycling exercise. While both systems use tactile feedback to enhance immersion, Bruun-Pedersen focused on using vibration to alter perceived physical exertion. In contrast, our project uses tactile feedback to mirror virtual interactions, such as object collisions, to enhance the user's sensory immersion. Both approaches highlight the importance of synchronizing tactile stimuli with other sensory inputs, although the end goals are different: where Bruun-Pedersen targets perceived exertion, this project emphasizes sensory coherence to support the user's sense of presence and immersion in the virtual environment [15].

As outlined in the previous section on audio, tactile feedback works in together with sound to create a fully immersive experience. Each tactile cue is matched with its auditory counterpart, ensuring that users not only hear but also feel the interactions occurring around them, reinforcing the sense of presence in the virtual world.

3.3.5 System integration and synchronization

As mentioned before in 3.2.3 and the two previous sections, the importance as well as the challenge arises in integrating the sensory feedback together. The system must provide synchronized multisensory feedback, meaning that audio and tactile stimuli are aligned with visual cues in the virtual environment. This synchronization between sensory modalities is central to the studies approach, as it allows us to study immersion in a non-interactive context, focusing on how well sensory cues alone can engage users. The design prioritizes the interplay between these sensory modalities, ensuring that they complement rather than compete with each other. For example, when a user observes an event in the virtual world that would naturally produce both sound and a physical sensation - such as an object hitting the glass cube - the system ensures that auditory and tactile feedback occur simultaneously. To achieve this, the system uses advanced audio processing techniques to spatialize sound accurately within the virtual environment, creating realistic soundscapes that enhance the user's sense of space. At the same time, tactile feedback delivered through the custom-built physical device is synchronized with these sounds to provide physical sensations that match the intensity and character of the auditory cues. In both cases, synchronization between sensory modalities is crucial, but the research objectives are different. While other mentioned studies explore the role of feedback in managing physical strain, this project focuses on creating a sensory experience that supports research into the impact of multisensory feedback on user immersion and presence. With the concept of the "Phantastic Sound Experience" clearly defined, the next step was to translate these design choices into a functional system. The core objective of combining auditory and tactile feedback to enhance user immersion has been established through integration of sensory modalities, a neutral yet engaging environment, and synchronized feedback mechanisms. The conceptual framework provides a sound basis for evaluating how these sensory inputs contribute to immersion and presence, but the success of this study depends on its technical realization. The following chapter focuses on the implementation phase, detailing how the hardware and software components of the system come together to create the immersive experience envisioned in the design. This includes the development of custom tactile devices, the synchronization of audio-visual-tactile feedback and the use of advanced audio processing technologies.

3.4 Scientific process

3.4.1 Engineering approach for VR

The engineering process serves as the foundation for the system's development, providing a structured framework for integrating the disparate components that collectively constitute the virtual reality experience. From a theoretical perspective, the engineering approach emphasizes the construction of a robust system that seamlessly integrates visual, auditory and tactile feedback, thereby enhancing user immersion. The system's design incorporates well-established virtual reality development platforms, including the Unity engine and Steam Audio. These have been selected on the basis of their capacity to deliver high-quality visual and spatial audio feedback. The flexible architecture of Unity permits the real-time rendering of dynamic three-dimensional environments, while Steam Audio offers sophisticated spatialization techniques that permit users to hear sounds from different directions, thereby enhancing the realism of the virtual world. A significant element of the engineering methodology is the incorporation of haptic feedback, utilizing haptic technologies to impart a sense of physical engagement within the virtual environment. The plan for the tactile component entails the utilization of vibration motors that translate low-frequency audio signals into physical sensations, thereby reinforcing the user's sense of presence. It is anticipated that this multisensory integration will enhance the system's capacity to fully immerse participants by synchronizing haptic responses with audio and visual cues. From a theoretical perspective, this engineering approach aims to create a cohesive virtual environment where sensory feedback systems work in harmony. It is essential that calibration of the various elements is carried out correctly, particularly in ensuring low latency and synchronization between audio and tactile stimuli, in order to avoid breaking the immersive experience.

3.4.2 Prototyping process

The system will adopt an evolutionary prototyping approach, thereby enabling the design to evolve in an iterative manner through cycles of testing, user feedback, and refinement. Evolutionary prototyping is a widely accepted method in software and system design, particularly in complex, interactive environments like VR, where user feedback is critical for refining the user experience. This methodology enables the system to commence with a fundamental prototype that incorporates the essential components, including visual rendering, spatial audio, and fundamental haptic feedback. This is followed by the implementation of incremental enhancements. The prototype will initially be evaluated in a controlled setting to ascertain the functionality of the fundamental systems, including the physics-based interactions, sound propagation, and tactile feedback mechanisms. Through evolutionary prototyping, the system is expected to evolve into a more immersive and responsive VR environment. Each iteration will aim to address specific design challenges identified during testing, ensuring that the final system provides a polished and seamless multisensory experience. The advantage of this method is its flexibility - it allows for constant adjustments without requiring a fully complete system at the outset, allowing for continuous improvement as the system evolves. Through evolutionary prototyping, the system is expected to evolve into a more immersive and responsive VR environment [86].

3.4.3 Evaluation methods

The evaluation of the "Phantastic Sound Experience" will be guided by qualitative evaluation methods, with a particular focus on understanding users' subjective experiences within the virtual environment. Theoretical models from human-computer interaction and virtual reality research, such as Witmer and Singer's work on presence and immersion, will inform the evaluation process. In the planned evaluation, participants will complete structured questionnaires based on established scales such as the Presence Questionnaire and the Immersive Tendencies Questionnaire. These instruments are designed to capture users' subjective responses to various aspects of the VR experience, including their sense of presence in the virtual world and their level of sensory engagement. For example, questions will assess how fully the environment engages the user's senses or how aware they remain of their physical surroundings during the VR experience. A Likert scale will be used for most questions, allowing users to rate their experience from 'strongly disagree' to 'strongly agree'. This will provide quantitative data that can be analyzed alongside qualitative insights from debriefing sessions. These sessions will give users the opportunity to elaborate on their experience, discussing factors such as comfort, immersion and any discrepancies between sensory inputs.

CHAPTER 4

Implementation

This chapter explains the implementation of the "Phantastic Sound Experience" based on the design described in the chapter before. It details the systematic translation of the design concept into an immersive virtual environment. It incorporates the integration of the physical device, including the deployment of vibration modules, and precise creation of dynamic sound landscapes for virtual reality. The requirements specified in Chapter 3.1 were closely studied to ensure strict alignment between the conceptual framework and practical implementation. The first part of this chapter describes the process of developing all basic components, namely the creation of 3D assets, sound and sensory feedback. The second part addresses their integration in the virtual world.

4.1 Virtual environment

The virtual world forms the core of the "Phantastic Sound Experience", providing a visually engaging and interactive environment that enables the sensory feedback systems. As discussed in Section 3.3.1 of the design chapter, the inspiration for the virtual environment comes from the architectural style of Ricardo Bofill, particularly his work on Muralla Roja. The selection of this design was required in order to provide geometric precision and minimalism to guarantee that the space has considerable aesthetic impact while remaining unobtrusive to the user. This approach supports the user's ability to immerse themselves in the environment rather than distracting them from the primary experience. In order to achieve this, all required elements had to be modeled, textured and composed in Blender, a open source 3D software that was chosen for the project. The primary structure of the virtual world is placed in an ethereal sky, disconnected from the ground to create a surreal, otherworldly environment. This design choice aims to enhance the sense of detachment from reality, which is key to deepening the user's immersion, as discussed in the Virtual Environment Design section. The central architectural feature is a cubic structure with rounded windows and rooftop outlets, reminiscent of Bofill's geometric and minimalistic designs that is shown in figure 4.1.

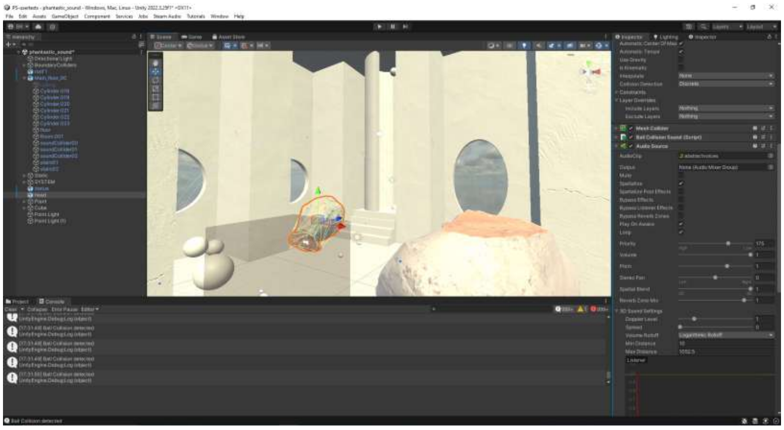


Figure 4.1: Final view in Unity

Within this environment, users are enclosed in a glass cube, which serves as their vantage point. The cube is both a physical boundary and a symbolic barrier, isolating the user from the dynamic external world while still allowing them to observe it closely. The glass walls provide transparency, while the stone foundation adds weight and realism to the structure, ensuring that it responds believably to physical interactions with other elements, such as the spheres. The spatial layout of the environment encourages passive interaction with dynamic objects, such as spheres that move within the space. These spheres are not only visually engaging but also functionally important, as they respond to audio cues and form a critical part of the dynamic feedback system. Their constant motion and interaction with the environment add to the evolving nature of the experience, offering users an ever-changing visual landscape to explore from their secure position within the cube.

4.1.1 Asset creation

The creation of the virtual environment's assets was done using Blender 4.0, chosen for its flexibility and advanced modeling tools, as well as its open-source nature. The use of Blender allowed for detailed modeling of both architectural structures and dynamic objects, ensuring that the virtual world maintained high visual fidelity while optimizing for performance in Unity, the game engine used for the implementation (discussed further in Section 4.4. The glass cube, staircases, circular platforms, and the spherical objects were created to not only reflect the minimalist aesthetic but also support the dynamic interactions that take place during the experience. The glass cube was a particular focus during the modeling phase, as it needed to convey both transparency and solidity. Its upper surface was modeled as clear glass, while the foundation was constructed with stone textures to ensure that it behaved realistically when interacting with the spheres. In Blender, the physics simulation features were employed to test the cube's response to these dynamic elements before exporting the models to Unity. Each element of the virtual environment serves both a functional and aesthetic purpose, contributing to the overall immersive experience. The spheres, which are central to the dynamic nature of the virtual world, were modeled to move freely within the space, reacting to both the physical properties of the environment and the audio cues that govern their behavior. The spheres are designed to introduce variability, their movement providing an evolving visual stimulus that enhances user engagement. The architectural elements, including the staircases and circular platforms, were designed not only to reflect Bofill's geometric elegance but also to function within the dynamic environment. The staircases guide the movement of the spheres, while the platforms provide visual balance and structure to the floating, surreal space. Each component was measured and constructed to align seamlessly with the interactions programmed in Unity, ensuring smooth animations and consistent user experiences.

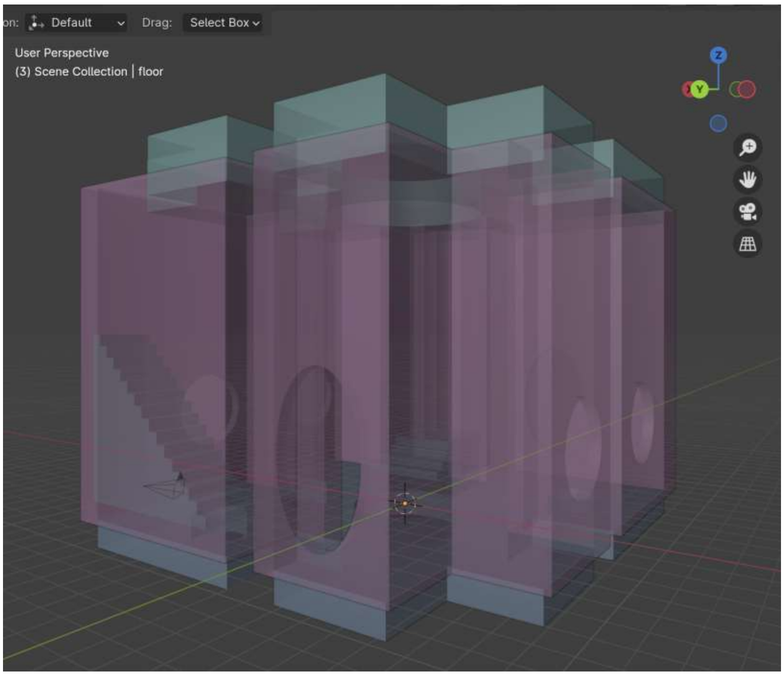


Figure 4.2: Rendering of the architecture in blender

4.1.2 Textures and Materials

Texturing played a critical role in bringing the virtual world to life. To maintain the minimalist aesthetic, the textures were kept simple but detailed enough to add depth and realism. The glass surfaces of the cube were textured to reflect light subtly, adding to the feeling of transparency and fragility, while the stone base was textured to provide contrast and weight. The textures were UV-mapped in Blender to ensure that they scaled appropriately when integrated into Unity, maintaining their realism without introducing visual artifacts.

For the architectural elements like the platforms and staircases, soft gradients and muted colors were used to reinforce the sense of tranquility, drawing attention away from the architecture and toward the dynamic elements such as the spheres and audio-responsive interactions. This texturing choice complements the audio and tactile feedback, allowing the visual elements to support the overall immersive experience without overwhelming the sensory inputs. The textures were prepared in blender and later rebuilt in unity.

4.2 Audio

The sound design principles of this project focus on creating a realistic audio environment that complements the visual and tactile elements of the virtual world. With advanced spatial audio technologies, the system ensures that sound reflects the acoustics of the real world and aims to improve the user's sense of presence as stated earlier in 2.3.1. The Steam Audio plugin plays a crucial role in spatializing sound in this virtual environment. With the help of binaural audio technologies, the scripts provide rotation and positioning tracking, enabling low-latency, physics-based audio that supports a wide range of VR hardware. This creates an immersive listening experience that adapts seamlessly to the user's movements and interactions. The soundscape can be separated into two categories: the ambient audio landscape and the sound effects. In the next section the creation of the ambient music is explained.

4.2.1 Conception

The concept of the soundscape was inspired by the space movie genre, with the objective of evoking the sensation of floating in an infinite atmosphere. This reflects the virtual environment's geometric and surreal architectural style, which removes the user from the physical resemblance of the real world. The sound is designed in such a way as to reinforce this sense of detachment, transporting users into a limitless, otherworldly space, thus enhancing both the aesthetic and emotional impact of the environment.

The central ambient track serves as the foundation of the soundscape and is constructed upon a 4/4 beat utilizing *higher frequencies*. This was crucial for future frequency separation. It was implemented in order to guarantee that the ambient sound does not interfere with the sound effects, which are primarily located in the *lower frequency range (below 80Hz)*. This separation enables the sound effects, such as impacts and collisions, which will be discussed in greater detail in the subsequent section on sound effects, to be prominent without being overwhelmed by the ambient music, thus ensuring a clear and balanced auditory experience.

In order to achieve this, the ambient soundscape was composed using a combination of synthesized and pre-made sounds. These sounds were layered and mixed in Ableton Live, which offers a variety of professional tools for sound synthesis and composition. The combination of soft, sweeping pads evokes the vastness of space, while melodic elements subtly guide the emotional journey of the user, encouraging a sense of curiosity and peaceful immersion. This layering technique aligns with the virtual world's design goals, helping to maintain a cohesive mood throughout the experience and ensuring that the audio reinforces the visual cues and the user's interaction with the environment.

4.2.2 Sound effects

In addition to the ambient soundscape, a variety of sound effects were created with the objective of enhancing the realism of interactions within the virtual environment. These serve as auditory feedback in the virtual world. The aforementioned sound effects were produced using the Foley technique, which is commonly employed in the production of films and video games. The objective of this technique is to create realistic, synchronized sounds that align with the on-screen actions. Foley work entails the manual recording of sounds utilizing everyday objects, which are then adapted in a creative manner in order to simulate the requisite audio for the given project.

The objective was to attain a high level of realism in the planning and execution of these sound effects. To illustrate, the sound of spheres colliding with glass was created by recording the impact of a tennis ball against a polymethylmethacrylate panel, which mimics the acoustic properties of glass. This approach guaranteed that the auditory representation of the collision was genuine and consistent with the physical interactions within the virtual environment. Similarly, the collision of spheres with concrete was replicated by dropping heavy objects onto concrete surfaces, while the dragging of con-

Figure 4.3: Layering of the ambient track in ableton

crete was simulated using two concrete blocks. Subsequently, the recorded sound effects were imported into Ableton Live for editing and preparation for integration into the game engine. The editing process entailed a series of pivotal steps to guarantee that the sound effects were not only realistic but also aligned with the audio design parameters for the project. A principal objective was to restrict the frequency range of these effects to below *80 Hz*, a crucial factor in maintaining the clarity of the ambient soundscape, which is predominantly comprised of higher frequencies. This separation also ensured that low-frequency sounds could be accurately translated into tactile feedback, thereby enhancing the physical sensations experienced by the user.

In Ableton Live, a variety of audio editing techniques were employed, including equalization, compression, and reverb.

- **Equalization** was a crucial technique for the isolation of low frequencies, which were integral to the functionality of the tactile feedback system. The use of the Audio Effect *EQ Eight* with the low-cut function turned out to be sufficient to cut out undesired frequencies

- **Compression** was employed to regulate the dynamic range of the audio, thus ensuring a uniform volume and impact despite the inherent variability in the original recordings.

- **Reverb** was employed to align the virtual environment's acoustics with those of the original recordings, thus ensuring that the sound effects appeared natural and integrated seamlessly into the space.

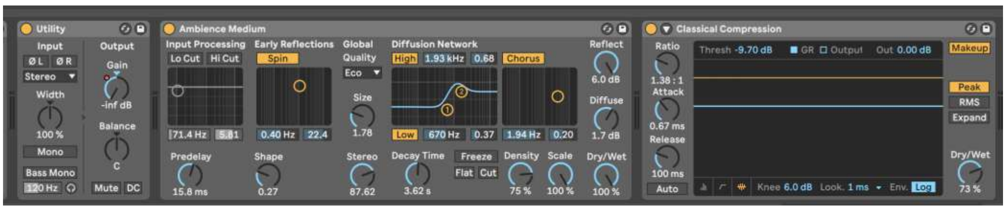


Figure 4.4: Example of effect use in Ableton live

These techniques employed during the audio production phase guaranteed that both the ambient music and sound effects were harmoniously integrated to enhance the immersive quality of the virtual world. This alignment of auditory feedback with visual and tactile elements served to reinforce the overall experience.

4.3 Physical setup and tactile feedback

This section outlines the design and construction of the physical setup, focusing on how the system was optimised to provide precise and synchronized haptic feedback to the user. It explores the connection between the tactile system and the virtual world, emphasizing the importance of synchronizing audio and vibration to maintain immersion.

The chapter also discusses the technical challenges encountered during implementation - such as vibration isolation and signal transformation - and how these were overcome to ensure consistent, responsive performance. This discussion lays the groundwork for understanding how the physical components support and enrich the virtual experience, building on the previous chapters that detailed the sensory elements of the virtual world.

4.3.1 Construction of the physical component

The design of the physical setup was focused on delivering precise and effective tactile feedback that enhances the user's immersion in the virtual world. The unit is built on a sturdy wooden panel mounted on a flexible metal table frame. This frame serves two key purposes: providing structural support and isolating vibrations. Isolating the vibrations ensures that they are concentrated on the user, preventing them from dispersing into the surrounding environment, which would otherwise diminish the effectiveness of the tactile feedback. The wooden panel was chosen for its durability and responsiveness, serving as the primary surface for translating audio signals into physical vibrations. A chair is securely fixed to the panel, offering the participant a stable seating position. The chair is anchored with robust screws and bolts to withstand the combined weight and vibrations produced during the experience, ensuring both comfort and stability for the user. The tactile feedback is driven by a vibration motor mounted beneath the wooden panel. The motor's central positioning ensures even distribution of vibrations, providing a consistent haptic experience regardless of where the participant is seated. This motor is connected to a Fischer amplifier, which processes the audio signals from the computer and converts them into the electrical signals needed to drive the motor.

The frame was built first, ensuring it was level and stable, followed by the mounting of the wooden panel using bolts and brackets to guarantee a firm connection. Once the panel was in place, the chair was fixed to the panel, and the vibration motor was installed. After construction, all connections between the motor, amplifier, and computer were tested to ensure safe, reliable operation.

4.3.2 The connection to the virtual world

The tactile feedback system was integrated with the virtual world through a direct connection between the computer's audio output and the Fischer amplifier. This ensures that the physical vibrations are synchronized with the audio cues from the virtual environment, which is essential for maintaining the immersive experience. The implementation follows the concept of the feedback loop illustrated in 3.2.3. An audio cable transmits real-time audio signals from the virtual environment to the amplifier, which processes them and drives the vibration motor accordingly. This real-time feedback loop ensures that every sound the user hears in the virtual space is accompanied by a corresponding tactile sensation, helping to solidify the perception of the virtual environment as real and tangible. A critical aspect of the system is low latency, the delay between producing a sound in the virtual world and the user perceiving the corresponding vibration. High

Figure 4.5: Construction of the physical component, adding the vibration motor

latency could break immersion, as the user might sense a disconnection between the sound and the tactile feedback. To avoid this, the system is designed to deliver vibrations almost instantaneously in response to audio cues, ensuring seamless synchronization.

4.3.3 Synchronization and performance

Achieving synchronization between the audio and tactile feedback was one of the primary challenges during implementation. Several strategies were employed to ensure smooth operation:

Real-time Audio Processing: The system processes audio in real time, ensuring that any sound produced in the virtual environment is immediately translated into vibrations. The Fischer amplifier was fine-tuned to minimize processing delays, ensuring that the tactile feedback was closely aligned with the audio cues.
Calibration and Testing: A comprehensive calibration process was conducted to ensure that the intensity and timing of the vibrations were aligned with the audio cues. Adjustments were made to the gain levels on the amplifier and the positioning of the vibration motor to ensure that the vibrations felt natural and were perceived in harmony with the audio.
Iterative Refinement: The tactile feedback system underwent several rounds of user testing and refinement. User input was invaluable in identifying discrepancies between the

Figure 4.6: Finished construction

audio and tactile sensations, leading to further adjustments that ensured the vibrations were both synchronized and intuitively perceived as part of the immersive experience.

4.3.4 Challenges and solutions in physical implementation

During the construction and integration of the tactile feedback system, several key challenges were addressed:

Vibration Isolation: It was crucial to prevent vibrations from dissipating through the floor or neighboring structures. This was resolved by using a flexible metal frame specifically designed to isolate and concentrate vibrations on the user.
Power Management: Ensuring consistent tactile feedback without power fluctuations or overheating was another challenge. The Fischer amplifier was selected for its reliability and capacity to handle real-time audio-to-tactile conversion without performance drops.
User Comfort: Delivering strong tactile feedback while maintaining user comfort was essential. The system was designed to distribute vibrations evenly across the wooden panel, preventing discomfort or fatigue during extended use. The placement of the chair and the motor were optimized to ensure that the vibrations felt natural without becoming

overwhelming.

By overcoming these challenges, the "Phantastic Sound Experience" successfully integrates the physical component with the virtual world, creating an immersive interaction where sound and touch work together to enhance the user's sense of presence. In order to enable the evaluation of sensory feedback, it is first necessary to bring together the topics that have been discussed in this chapter thus far. The next section explores the implementation of the virtual world in VR, detailing how audio and sensory feedback were integrated to enhance the immersive experience.

4.4 Implementation of the experience in Unity

The most important step was to combine all the previous parts into one interactive experience. The next phase of the development process involved importing the created models into Unity 2022 LTS, the chosen game engine for the project. Unity was chosen as the game engine for the project because of its extensive virtual reality support, flexibility and robust community resources. The Steam VR package was integrated into Unity to provide the necessary basic VR functionality and ensure compatibility with the chosen hardware, the Vive Pro 2. The Universal Render Pipeline (URP) was used to optimize performance and visual quality. The URP enables the creation of highly efficient render pipelines that are tailored to the needs of the VR environment. This approach allows the delivery of high fidelity visuals while maintaining the performance levels required for real-time rendering. A key visual component of the virtual environment is the sky, which is represented by a high dynamic range imaging sky map. The sky map has two functions: it represents the environment and is the primary source of lighting. The lighting is soft and immersive, enhancing the visual atmosphere of the virtual space. The architectural structure created in Blender was imported into Unity as an FBX file, ensuring that all details and textures were preserved during the transition. Subtle lighting was then configured and baked into Unity to improve performance. The lighting baking process is used to pre-calculate lighting interactions, reducing the computational load at runtime and ensuring that the virtual world remains responsive and fluid.

4.4.1 Key systems

To facilitate interactivity within the "Phantastic Sound Experience", several systems were implemented to handle dynamic object behavior and audio integration. Two core components of this system are the **Audio Manager** and the **Sphere Generator**, both working together to create an evolving, responsive environment.

Audio Manager: This component is important for the rendering of sound within the environment, it is responsible for loading, playing and analysing audio. The audio track playing in the background is subjected to analysis using Fast Fourier Transform (FFT) functionality, which facilitates the decomposition of audio into its constituent frequency components. The Audio Manager is able to detect peaks in the audio signal, which it then uses to trigger events within the virtual world. These events for example are responsible for triggering the sphere generator. They also trigger other scripts that are responsible for the movement of colliders. It also oversees the management of audio sources, including the ambient track that serves as the foundation for the entire experience.

Sphere Generator: The Sphere Generator is the component responsible for creating and managing the spheres within the environment. In response to audio peaks, the Sphere Generator creates new spheres based on data received from the Audio Manager, providing a dynamic link between the visual activity in the room and the music. Each sphere is assigned physical properties that determine how it interacts with other objects in the environment.

Rigid Body System: The Rigid Body System is a core component of Unity's built-in physics engine and plays a crucial role in the simulation of physical interactions. By assigning a *RigidBody* component to each sphere, the system allows the spheres to behave according to realistic physical principles such as gravity, mass and velocity. Physical materials are used to define specific properties such as bounce, friction and mass, which determine how the spheres react to collisions and interactions within the environment. For example, the degree of elasticity controls how much the spheres bounce off surfaces, while friction affects how they slide or roll when in contact with other objects. To enable collisions, colliders have been strategically placed on all relevant elements within the virtual environment. This ensures that the spheres do not pass through walls or other objects, maintaining the illusion of physical space. Different types of colliders - such as box colliders for flat surfaces and mesh colliders for more complex shapes - helped define these boundaries and ensured accurate and realistic collision detection. In addition, Unity's physics system allows for dynamic object interaction, meaning that as spheres collide with each other or with the environment, the physics engine calculates the responses to these collisions in real time, including the momentum and trajectory of the sphere after impact. This interaction further enhances the realism and immersion of the virtual world, contributing to a more engaging and believable experience for users.

Seamless Integration for Immersion: These systems work together to create an immersive, dynamic environment. As the ambient track plays, the Audio Manager continually analyzes the music, triggering the Sphere Generator to fill the space with spheres that interact with the environment and the glass cube housing the participant. As these spheres collide with the cube, they apply pressure that causes subtle movements, adding to the realism of the user's experience. The dimensions of the room and the sphere sizes were adjusted through iterative testing to ensure the space fills over the five-minute duration of the ambient track, offering users an immersive and constantly evolving experience.

4.4.2 Audio in unity

Each component of the virtual environment that generates audio is equipped with a Steam Audio Source script. The script ensures that the sound is distributed correctly, taking into account factors such as position, air absorption and occlusion. By replicating the physical distribution of sound through the audio source scripts, sounds can be emitted from specific locations and resonate as they would in the physical world. The incorporation of Steam Audio not only enhances the realism of the virtual environment, but also ensures that audio feedback is accurately aligned with the user's position and interaction. The spatial audio technologies used provide users with a highly immersive experience, with sounds triggered by virtual events resonating from appropriate locations to create a coherent and convincing soundscape.

4.4.3 Setup of Steam Audio

Integrating Steam Audio into Unity was critical to creating an immersive audio experience. The process began with the Steam Audio package, a tool set designed for spatial audio in virtual environments. Its advanced features made it an appropriate choice for this project.

The following section provides an overview of the steps required to integrate Steam Audio into a Unity project.

1. The installation process is as follows: The first stage of the process involved downloading and importing the Steam Audio package into the Unity project. This was achieved by using Unity's Package Manager to ensure that all the necessary assets and scripts were available for integration into the virtual environment.

2. The next step is to configure the Steam Audio Manager. Following the installation process, a Steam Audio Manager object has been created within the Unity scene. The Steam Audio Manager is responsible for global audio settings, including the handling of sound propagation and occlusion. The Steam Audio Manager was configured to meet the specific requirements of the project, including modifying the speed of propagation and creating an environment conducive to accurate reverberation and reflections.

3. Appending Steam audio source scripts: Next, a Steam Audio Source script was applied to each audio-emitting object in the virtual environment. This script allows for accurate spatialization of sound, taking into account the 3D position of the sound source in relation to the user. Key settings such as distance attenuation, air absorption and occlusion were calibrated to ensure that the sound behaved as realistically as possible.

4.4.4 Configuration

To create a cohesive audio environment, specific sounds were placed and configured in the Unity project to facilitate the desired listening experience. The ambient track, which serves as the foundation for the audio experience, was assigned to the Audio Manager object. The object was placed at the center of the virtual environment to ensure an immersive and comprehensive listening experience. Placing the ambient track in this way ensures that the sound is evenly distributed throughout the room, creating an immersive experience that evokes a sense of curiosity and tranquility. In terms of sound effects, each was assigned to the appropriate object within the scene. For example, collision sounds were assigned to the spheres as they moved and interacted within the virtual environment. The Steam Audio Source script attached to these objects ensures that the collision sounds are not only triggered at the right moment, but are also spatially localized according to the location of the collision relative to the user's position. The precise placement and configuration of the sounds contributes significantly to the realism and immersion of the experience. Managing multiple audio sources in a virtual environment requires planning to avoid overload and ensure clarity. It was important to provide the right mix of sounds such as collisions while maintaining the ambient track. Steam Audio allowed precise calibration of each sound source, ensuring that users hear relevant sounds based on their movements.

4.4.5 Optimizing for integration and performance

Given the real-time nature of VR, it was important to optimize audio performance to maintain a seamless and immersive experience. Steam Audio's real-time processing capabilities were used to ensure minimal latency in sound propagation and spatialization. Resource management techniques, such as eliminating distant sound sources or modifying sound quality based on the user's distance from the source, were also used to maintain optimal performance without compromising audio quality. Steam Audio's advanced features, including occlusion and sound propagation, were instrumental in achieving realism. The occlusion feature was used to simulate the way sound is blocked or absorbed by surrounding objects, adding depth and realism to the audio experience. For example, the sound of a bullet colliding with a surface can be partially muffled if another object is in the way, as would happen in the real world. Environmental effects such as reverb have also been carefully implemented to simulate the acoustics of different materials, ensuring that each room in the virtual environment has a distinctive acoustic signature. It was important to integrate the audio with other sensory systems, particularly tactile feedback, to create a unified and coherent experience. To illustrate, when the user collides with the glass cube, they not only hear the impact, but also experience a corresponding vibration through the synchronized haptic feedback system. To achieve this, the every component had to be optimized for performance to avoid any lag or disruption.

4.4.6 First iteration

The first iteration of the "Phantastic Sound Experience" marks the initial implementation of the project, integrating all sensory feedback mechanisms - visual, audio and tactile. This version will serve as the basis for the following user testing, which will assess the effectiveness of the immersive experience. While the core systems are in place, further fine tuning is required to optimize the sensory feedback and improve overall performance. With the first iteration of the "Phantastic Sound Experience" complete, the next step was to validate and refine the core systems - visual, audio and tactile feedback - through user testing. While the technical components had been successfully integrated and optimised, real-world testing was essential to assess how these systems worked together to create an immersive experience for participants. The user testing phase provided an opportunity to evaluate the effectiveness of the design, gather qualitative and quantitative feedback and identify areas for improvement. By systematically reviewing how users interacted with the virtual world, the iterative process aimed to fine-tune the system and improve both its performance and overall immersion. The next chapter will focus on conducting user tests and iterating on the design based on the feedback gathered to improve the immersion and interactivity of the system.

4.5 User tests

User testing of the "Phantastic Sound Experience" was conducted over a two-day period with two participants who had a moderate level of experience with virtual reality. The primary objective of these tests was to evaluate the effectiveness of the system design in order to gain insight into how to best calibrate the system. Key topics included the physical, auditory and tactile components of creating an immersive and engaging virtual environment. The tests aimed to identify areas of strength and potential for improvement by systematically varying key parameters across sessions.

Each participant interacted with the virtual environment for five minutes during three different sessions. The first session presented the baseline, the second and third session were with improved parameters after the given feedback. Between each session, specific parameters were adjusted to explore their impact on the overall experience. Parameters examined included the number of spheres generated, the physical interactions between the spheres and the glass cube (including the movement and weight of the cube), and the intensity of both the sound and corresponding vibrations generated by the haptic feedback system.

4.5.1 Key Findings and analysis

The user tests provided valuable insights into how different elements of the virtual experience impacted participants' immersion and enjoyment, while also highlighting areas for improvement. The key conclusions drawn from the feedback are as follows:

General experience and pacing: Participants responded positively to the overall pacing of the experience, particularly the gradual filling of the room with spheres over five minutes. The pacing was considered well-balanced, maintaining engagement without becoming monotonous. The accumulation of spheres provided a dynamic interaction, which participants found kept their attention throughout the session. However, participants also noted that while the progression was engaging, the virtual environment lacked interactive components, leading to a sense of constraint. They expressed a desire for a more complex and varied setting that would increase immersion and interaction.

Physical Interaction and cube movement: While the physical interaction between the spheres and the glass cube was initially appreciated, the force of the collisions was found to be excessive. Participants reported that the exaggerated movement of the cube reduced the realism, detracting from the sense of immersion. The movement was too significant to align with the otherwise controlled and stable environment, breaking the illusion of the experience. Both participants suggested that adjusting the impact forces could help create a more believable and immersive interaction.

Sound distribution and intensity: The sound distribution within the virtual space was generally well-received, as it created a cohesive auditory environment. However, participants noted that the intensity of certain sound effects, particularly those triggered by collisions, was overwhelming. Excessive volume occasionally disrupted immersion and made it difficult to focus on other sensory inputs. In addition, the sounds produced by the colliding spheres were perceived as confusing and overly repetitive. Participants described the auditory clutter as detracting from the experience, particularly when trying to distinguish between meaningful interactions, such as impacts on the glass cube, and less relevant events. Furthermore, the short duration of impact sounds was found to reduce realism, as participants expected these sounds, especially those involving the cube, to resonate for a longer period.

Vibration feedback and tactile response: The tactile feedback provided by the vibration motor was perceived as too weak, limiting its ability to fully enhance the immersive experience. Participants appreciated the added dimension that vibrations brought to the interaction but felt that the feedback lacked intensity, diminishing its overall effect. Both participants suggested that stronger and more calibrated vibrations could significantly improve immersion by better aligning with the visual and auditory elements. The mild vibrations did not adequately convey the physicality of the virtual interactions, and more pronounced tactile feedback was recommended to better simulate the environment.

Conclusions and recommendations for improvement: Overall, the experience was positively received, with participants praising the concept and the integration of multiple sensory modalities. However, several areas for improvement were identified, particularly the need for better synchronization and calibration of feedback systems. Adjusting the intensity of the cube's movement, refining the sound design for clarity and realism, and enhancing the tactile feedback were key suggestions for future iterations. Additionally, participants recommended increasing the complexity of the environment by incorporating more interactive elements to foster deeper engagement. Addressing these points would help in creating a more cohesive, immersive, and satisfying virtual experience.

4.5.2 Resulting changes based on feedback

In response to user feedback, several key modifications were made to enhance the virtual experience and address issues raised during testing. These improvements aimed to create a more immersive and balanced experience by refining the environment, physics, audio, and tactile feedback systems.

First, the environment was enriched with additional elements such as statues and decorative objects to increase visual variety and interactivity, which can be seen in 4.7. These additions not only enhanced the aesthetic appeal but also contributed to a more complex and engaging experience, addressing participants' feedback about the simplicity of the original setup.

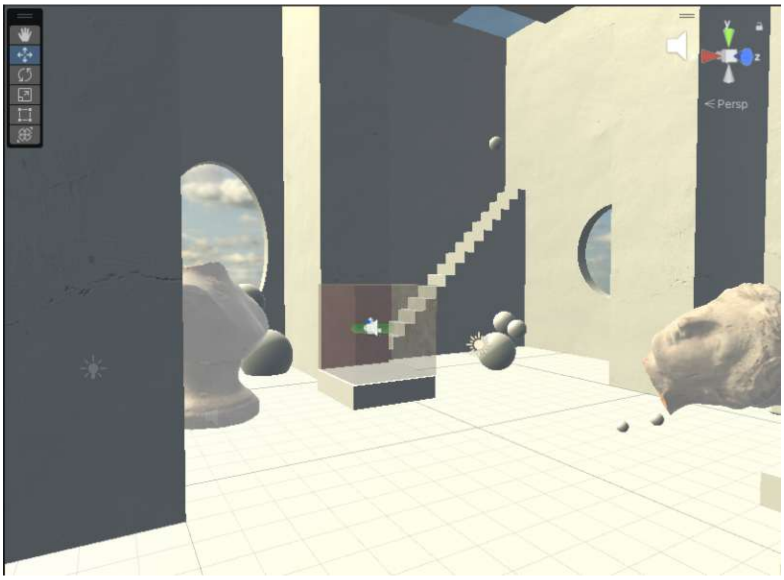


Figure 4.7: View of the added statues and the glass cube the participants sit in

To further enhance interactivity, the physics of one-third of the spheres were modified to float independently of gravity. This adjustment introduced new dimensions of movement, making the virtual world more dynamic and visually captivating. These floating spheres offered participants a varied and visually appealing interaction, improving overall immersion.

The auditory environment also underwent significant refinement. Sphere-to-sphere collision sounds were removed to eliminate auditory clutter, focusing the soundscape on more meaningful interactions, such as the collisions of spheres with the glass cube. Additionally, the impact sounds of the cube were adjusted to trigger only when the cube was in motion, reducing unnecessary audio triggers and enhancing the clarity of sound cues. This focused sound design helped create a more immersive and cohesive auditory experience.

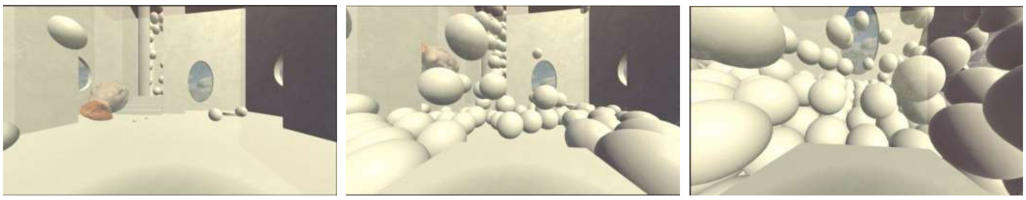
In terms of tactile feedback, the intensity of the vibrations was increased by adjusting the amplifier gain, leading to a more pronounced and perceptible haptic experience. This enhancement ensured better synchronization between the visual, auditory, and physical elements, contributing to a more immersive and tangible interaction with the virtual environment.

These changes collectively aimed to create a more immersive and engaging virtual reality experience, addressing key feedback points from the user tests while retaining elements that were positively received. By improving the visual, audio, and tactile components, the system now offers a more balanced and captivating experience that aligns with the project's goals of enhancing immersion through sensory feedback.

4.6 Improved system

The refined "Phantastic Sound Experience" represents a cohesive and well-integrated system that blends visual, auditory, and tactile elements to create an immersive virtual reality environment. The modifications based on user feedback, such as adding dynamic visual elements and enhancing tactile feedback, have significantly improved the system's performance and user experience. Visually, the environment strikes a balance between realism and simplicity, allowing users to engage without being overwhelmed. The introduction of dynamic, interactive elements like floating spheres and statues increases the system's engagement factor. These elements provide visual variety while maintaining a clean, structured design.

The audio system, powered by the Steam Audio plug-in, delivers a realistic 3D soundscape that enhances user immersion by accurately tracking and adapting to movements within the environment. Binaural audio techniques ensure precise sound spatialization, and the refined sound cues align perfectly with both visual and tactile elements. Tactile feedback, driven by a calibrated vibration motor, plays a crucial role in enhancing the user's sense of presence. The vibrations are now stronger and more synchronized with the audio and visual elements, offering a more cohesive multisensory experience. This real-time translation of audio signals into physical vibrations strengthens the user's connection to the virtual world, contributing to a more believable and immersive experience.



(a) view after 30 seconds (b) view after 120 seconds (c) view after 240 seconds

Figure 4.8: Views of the final simulation

In conclusion, the improved "Phantastic Sound Experience" presents a more balanced virtual world for evaluating the impact of sensory feedback on user immersion and presence. By integrating visual, auditory, and tactile feedback, the system offers a robust platform for further research into the role of multisensory experiences in virtual environments. How this platform was used to evaluate the impact of the sensory feedback will be discussed in the next chapter.

CHAPTER 5

Evaluation

This chapter presents the evaluation including data collection, results and discussion. The aim of this evaluation was to assess the effectiveness and usability of the Phantastic Sound Experience system, focusing on key metrics such as user engagement, presence, immersion and overall satisfaction. The revised implementation of the system was used to explore how the integration of 3D audio and tactile feedback enhances the user experience in virtual reality. Both quantitative and qualitative methods are used to evaluate the performance of the system in relation to its design goals. Special emphasis will be placed on the impact of multimodal sensory input - including visual, auditory and tactile feedback - and its role in enhancing immersion, presence and interaction. By analysing the collected data and comparing the results with existing research, insights will be gained into how well the system achieves its objectives and contributes to a broader understanding of sensory feedback in VR.

5.1 Setup

The set-up for evaluating the "Phantastic Sound Experience" was designed to ensure that both the technical and participant conditions were optimised for testing the immersive qualities of the system. The evaluation had two main components: the technical setup, which focused on providing high-quality audio and tactile feedback, and the participant setup, which ensured a diverse and prepared group of individuals.

The technical setup used state-of-the-art hardware, including the Vive Pro 2 headset for high-resolution visual and spatial audio feedback, and a custom-built haptic system for tactile feedback. A controlled environment ensured that participants could fully engage with the virtual environment without external distractions. On the participant side, care was taken to select individuals with varying levels of familiarity with VR technology. By combining state-of-the-art technical configurations with a well-balanced participant pool, the setup aimed to provide reliable data on how effectively the "Phantastic Sound Experience" met its objectives in terms of immersion, presence and overall user satisfaction.

5.1.1 Technical setup

The technical setup for the Phantastic Sound Experience evaluation was designed to provide ideal conditions for testing the immersive qualities of the system, particularly its audio and haptic feedback components. The primary hardware used for the evaluation was the Vive Pro 2 headset, chosen for its high-resolution display and advanced binaural audio capabilities. The headset was integrated with Steam Audio to provide spatial audio, allowing users to experience realistic 3D soundscapes that responded to their movement and interaction within the virtual environment. To provide haptic feedback, a vibration motor was mounted under a custom-built chair attached to a wooden panel. The motor was powered by a Fischer amplifier, which ensured that low frequency vibrations were synchronized with the audio cues. This setup provided users with a consistent and responsive tactile experience, enhancing their sense of presence and interaction within the virtual world. The evaluation was conducted in a empty room without noise interference. This controlled environment ensured that participants were fully immersed in the VR experience without external distractions. The room audio configuration used binaural audio output from the Vive Pro 2 headset. Steam Audio managed sound propagation and occlusion, simulating real-world auditory experiences in the virtual environment. Real-time reverb and occlusion effects were applied to ensure that the sound dynamically adapted to the user's movements and interactions, enhancing the realism of the experience.

5.1.2 Participant setup

The evaluation involved 12 participants between the ages of 21 and 36, selected to represent a diverse demographic with varying levels of familiarity with Virtual Reality technology. This age range was chosen to ensure that both experienced users and those less familiar with immersive systems were included, providing a balanced perspective on the usability and effectiveness of the "Phantastic Sound Experience". No previous experience of audio engineering or VR was required, although participants were asked about their general familiarity with VR systems and audio-based experiences. The selection criteria aimed to avoid bias towards audio experts or novices, instead focusing on a broad user group to ensure usability of the system across different backgrounds. Each participant was given detailed information about the nature of the VR experience, including any potential auditory or tactile discomfort. Informed consent was obtained before the evaluation began. Participants were also informed that they could withdraw at any time. Volume levels were pre-calibrated to ensure comfort, but participants were allowed to adjust the settings if necessary. The participants were divided into two groups - Group A and Group B - of 6 people each. This split allowed for comparative analysis, with each group experiencing different variations of the "Phantastic Sound Experience" to evaluate the impact of the sensory feedback.

Figure 5.1: Test Run

5.2 Evaluation methodology

This section outlines the key metrics used in the evaluation, including user experience, immersion and motion sickness, and highlights the importance of these factors based on previous research in human-computer interaction and virtual reality. The data collection process is based on a standardized questionnaire to ensure consistency, followed by thorough statistical analysis to compare performance across different user groups. Finally, the procedure for conducting the evaluation is detailed, emphasizing consistency in participant setup, interaction with the virtual world, and post-session debriefing to capture comprehensive feedback.

Through this methodology, the study aims to provide empirical evidence on how sensory feedback affects the VR experience, contributing to both system improvements and the wider academic discussion on immersive technologies.

5.2.1 Evaluation metrics

The evaluation focuses on key metrics to assess how effectively the "Phantastic Sound Experience" meets its objectives. These metrics are based on established research in human-computer interaction, presence and immersion in VR, ensuring a comprehensive evaluation of the system's performance and user experience.

Presence: Presence is a critical measure of how "real" the virtual environment feels. It is assessed using the Presence Questionnaire, which assesses sensory fidelity and user involvement. Research by Witmer and Slater [89] emphasizes the importance of presence in VR systems, as it has a direct impact on user engagement and task performance.

Immersion: The impact of high-resolution displays and 3D audio is evaluated based on the user's sense of being immersed in the virtual environment. Research by Slater and Wilbur [68] and Hendrix and Barfield [37] role of visual fidelity and spatial audio in enhancing the immersive experience. The evaluation will focus on how effectively these elements contribute to a seamless sense of presence.

Motion sickness: A custom questionnaire assesses physical discomfort, including symptoms such as nausea and dizziness. Motion sickness is a critical factor in VR usability, and understanding its impact helps ensure the system is comfortable for extended use.

Emotional Response: Participants' emotional responses (e.g. excitement, fear, enjoyment) are tracked to assess the affective impact of the VR experience. This metric helps to measure the emotional connection users form with the virtual environment, which is essential for measuring engagement and immersion.

Effectiveness of sensory feedback: The effectiveness of the sensory modalities is measured by how they enhance the overall VR experience. Tactile feedback will be evaluated for its contribution to haptics and realism, while 3D sound will be evaluated for its ability to create spatial atmosphere, improving sound localization and overall engagement.

By focusing on these areas, the evaluation aims to provide a comprehensive understanding of the system's strengths and areas for improvement. These metrics not only assess the performance of the VR system, but also contribute to a broader understanding of how sensory feedback influences user engagement, immersion and presence in virtual environments.

5.2.2 Data collection

The data collected for this evaluation is based on a questionnaire adapted from the Presence Questionnaire (PQ) and the Immersive Tendencies Questionnaire (ITQ), which were developed by Witmer and Singer [90]. These instruments, which have gained considerable recognition in the field, have been designed to assess the extent of presence and immersion in virtual environments. The PQ is specifically designed to assess the sense of being present, whereas the ITQ is intended to examine individual tendencies towards becoming immersed in virtual environments. In order to assess key aspects of the "Phantastic Sound Experience", the questionnaire was tailored accordingly. Questions as "How aware were you of your actual physical surroundings while in the VR environment?" and "How effectively did the virtual environment engage your senses?" were derived from the PQ and adapted to suit the context of this study, thus maintaining a focus on sensory fidelity and engagement as suggested by Witmer and Singer. Their work emphasizes that presence arises from a combination of directed attention, sensory input, and environmental immersion. The impact of sensory feedback was assessed by incorporating specific questions for Group B, such as "To what extent did the tactile sensations align with your visual and auditory perceptions?" and "Please rate the efficacy of the tactile feedback in enhancing the realism of the virtual reality experience." This focus is consistent with the concept of "sensory factors" as outlined in Witmer and Singer's framework, the specific questions are shown in the appendices A. This provides a solid foundation to explore if the integration of multimodal feedback can significantly enhance the sense of immersion and presence by engaging multiple senses in a coherent manner. The data from both groups were subjected to descriptive statistical analysis, with metrics such as the mean, median, and mode providing insights into the overall user experience. A t-test was employed to conduct statistical comparisons between Group A (without sensory feedback) and Group B (with sensory feedback), with the objective of identifying significant differences, particularly in how users rated immersion and presence. The results demonstrate a trend where multimodal sensory feedback was found to enhance the sense of presence and immersion, thereby supporting the original hypotheses and aligning with the empirical findings from Witmer and Singer's research on sensory engagement and virtual environments.

5.2.3 Procedure

The evaluation procedure was designed to systematically collect data on immersion, presence, motion sickness and the effectiveness of sensory feedback in the Phantastic Sound Experience. Each test session followed a structured format to ensure consistency and reliability of data collection.

1. Introduction and briefing: Each session began with a 15-minute briefing where participants were introduced to VR and informed about the specific research focus areas: immersion, presence, motion sickness and sensory feedback. This briefing helped to contextualise the experience for the participants and ensure that they understood the key aspects they were evaluating.

2. Setup and calibration: Participants were seated and the VR system was individually calibrated to ensure optimal visual and auditory performance. This step was critical to ensuring a consistent experience for all users.

3. Virtual world interaction: Participants spent five minutes immersed in the Phantastic Sound virtual world. This duration was chosen to allow sufficient time to explore the VR environment while minimizing the risk of fatigue and over-stimulation.

4. Interview with questionnaire: Following the session, participants completed a questionnaire designed to collect feedback on the following areas:

- Presence: Measured the extent to which participants felt present in the virtual world, including sensory involvement and realism.

- Immersion: Assessed how engaged participants felt within the virtual environment and the quality of the visual and auditory experience.

- Motion sickness: Evaluated any symptoms of discomfort, such as nausea or dizziness, experienced during the VR session.

- Qualitative feedback: Participants were encouraged to provide additional comments and suggestions for improvement.

For Group B, an additional section of the questionnaire focused on the effectiveness of sensory feedback, in particular how tactile feedback enhanced the sense of touch and realism.

5. Debriefing: After completing the questionnaire, participants were debriefed to discuss their overall experience. This provided the researchers with valuable qualitative insights and allowed for further exploration of any specific issues or suggestions for system improvements.

5.3 Results

This section presents the results of the evaluation of the "Phantastic Sound Experience". The results are divided into three parts: quantitative data, qualitative feedback and a comparison with the initial hypotheses. The quantitative analysis provides statistical insights into key user experience metrics such as immersion, presence and motion sickness, comparing the performance of Group A (without sensory feedback) and Group B (with sensory feedback). The qualitative results provide a deeper understanding of participants' reactions, both positive and negative, to their experience in the virtual environment. Finally, a comparison with the study hypotheses will assess whether the sensory feedback system met the expectations set during the design phase. This analysis will help determine the overall effectiveness of integrating multimodal feedback and inform future VR developments based on the findings.

5.3.1 Quantitative results

The quantitative data collected from the study was analyzed using descriptive statistics such as mean, median and mode, supplemented by a t-test to compare the performance of groups A and B. These statistical measures provide insight into central tendencies and variability, giving a clear picture of the user experience across the two conditions.

Presence: The sense of presence, measured by the Presence Questionnaire, revealed a difference between the two groups, with Group B showing an average mean score of 3.5 compared to Group A's 2.92. This indicates that the multimodal feedback, particularly the combination of 3D audio and tactile feedback, contributed to a slight increase in the participants' perception of being 'present' in the virtual environment. However, the t-test results did not show statistical significance, meaning that the observed difference between the groups, while present, was not strong enough to confirm a significant impact of the sensory feedback on presence.

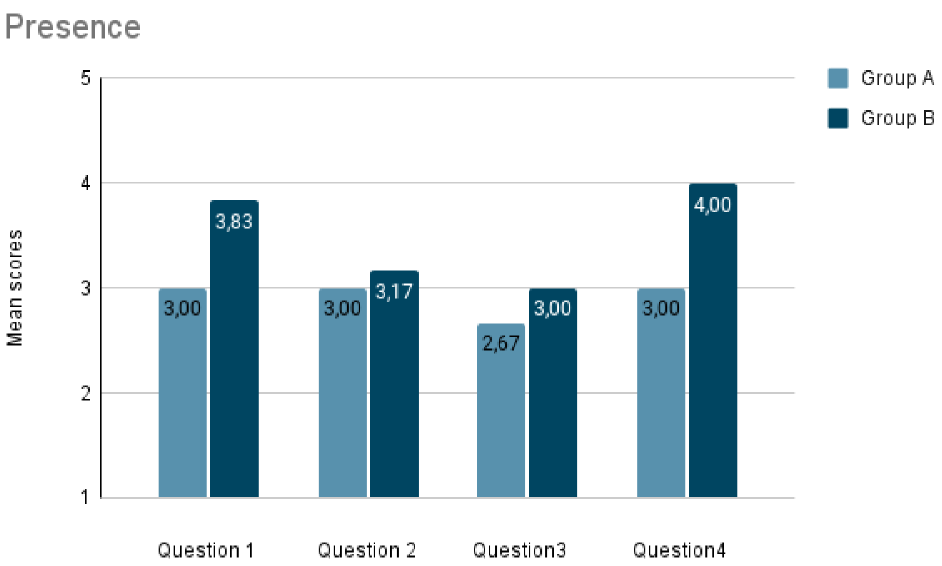


Figure 5.2: Summary of answered questions

Questions in 5.2

Question 1: How strongly did you feel 'present' in the virtual environment during the experience?

Question 2: To what extent did you feel like you were 'inside' the virtual world rather than merely observing it?

Question 3: How aware were you of your actual physical surroundings while in the VR environment?

Question 4: How effectively did the virtual environment engage your senses?

Table 5.1: T-Test Values for Presence Questions

Question	Q1	Q2	Q3	Q4
Presence	0.20	0.79	0.67	0.17

Immersion: Group B (with sensory feedback) reported a slightly higher level of immersion, with an average mean score of 3.78 compared to 2.89 in Group A. This lends support to the hypothesis that the integration of tactile and auditory feedback would enhance user engagement. Group B participants reported a heightened sense of physical involvement in the virtual environment, attributing this to the synchronized tactile vibrations and sound. Furthermore, comments regarding time perception indicate an enhanced sense of immersion. Several participants reported losing track of time or feeling absorbed in the experience. Descriptions such as "I was fully absorbed into the virtual reality" illustrate the engagement experienced by Group B. In contrast, Group A, which did not receive sensory feedback, reported less immersive experiences, with participants frequently maintaining a clear awareness of time or external surroundings. Some participants in Group A observed that "nothing really happened" or that they were aware of sounds from their environment, which made it more challenging to lose track of time. Although the t-test for the third question indicated a statistically significant result, the observed difference between groups was not sufficiently pronounced to be considered a definitive indicator, thereby limiting the extent to which these findings can be interpreted with certainty.

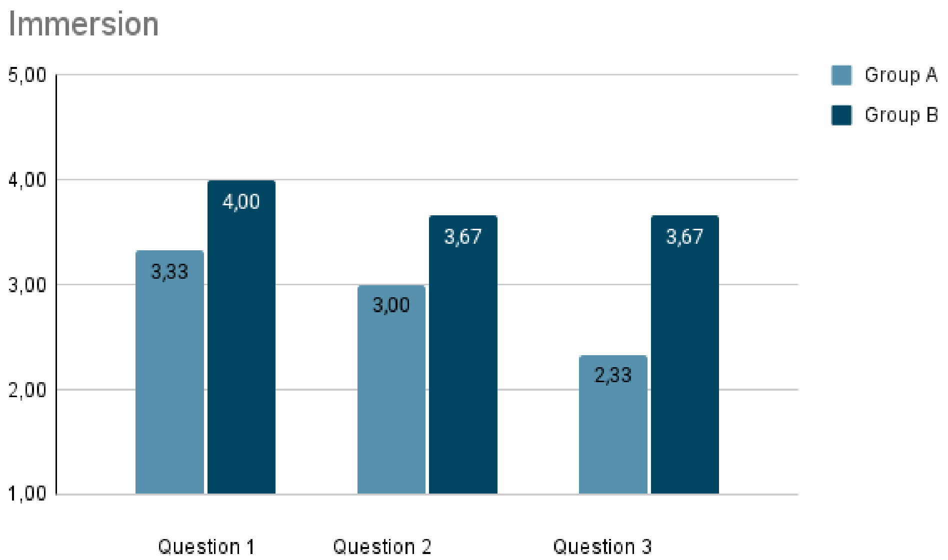


Figure 5.3: Summary of answered questions

Questions in 5.3

Question 1: How would you rate your level of immersion while being in the virtual environment?

Question 2: How engaging did you find the VR experience overall?

Question 3: To what degree did the virtual environment replace your real-world sensory experiences?

Table 5.2: T-Test Values for Immersion Questions

Question	**Q1**	**Q2**	**Q3**
Immersion	0.15	0.34	0.02

Motion sickness: The assessment of motion sickness was based on the severity of the symptoms experienced by the participants, who rated their experience on a scale from 0 (no symptoms) to 5 (very strong symptoms). The data for Group A and Group B are presented in the following:

Group A (without sensory feedback) exhibited a mean motion sickness rating of 2.1, indicating moderate symptoms. The range of responses spanned from no symptoms (0) to strong symptoms (4). Group B (with sensory feedback) demonstrated a lower mean rating of 1.5, indicating a generally lighter experience of motion sickness. Participants in this group exhibited fewer symptoms overall, with responses primarily in the lower range of the scale (0-2).

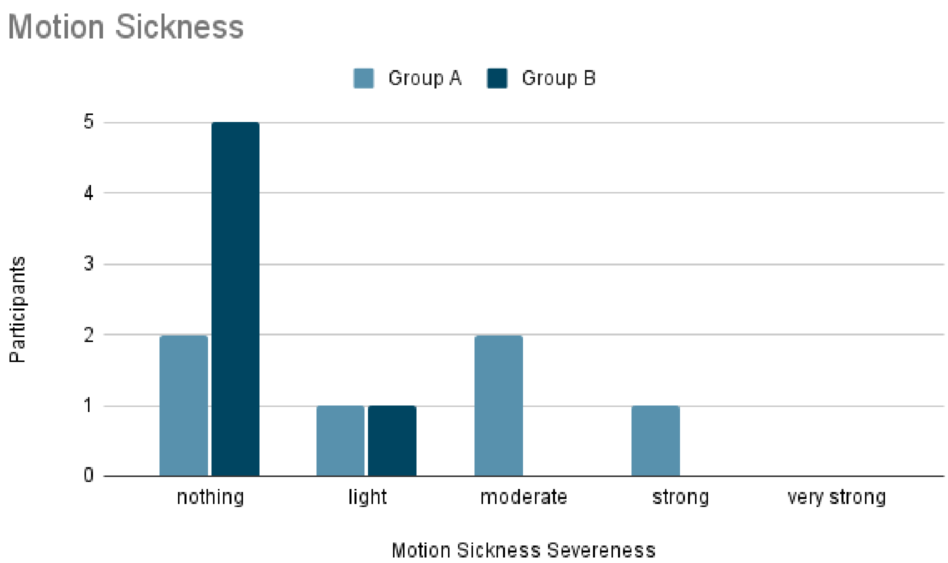


Figure 5.4: Comfort and motion sickness

Emotional response: The emotional responses of participants in Groups A and B revealed notable differences in the impact of the virtual experience on their emotional states. Group B, which received sensory feedback, reported higher emotional intensity, with an average intensity score of 3.33, in comparison to Group A, which reported an average intensity score of 2. Participants in Group B expressed a range of emotions, including excitement, calmness, and curiosity, with notable instances of relaxation and happiness. Furthermore, this group reported a stronger connection to the experience, with emotions such as surprise and excitement featuring prominently. In contrast, Group A, which did not receive sensory feedback, reported a reduction in emotional intensity, with calmness and curiosity being the predominant feelings. Although some participants in Group A reported experiencing emotions such as anxiety and excitement, the overall emotional engagement was found to be lower. This indicates that the provision of sensory feedback in Group B significantly enhanced the emotional depth and engagement with the virtual environment. These findings indicate that the provision of multimodal sensory feedback can evoke more pronounced emotional responses, thereby facilitating a more immersive and emotionally resonant experience.

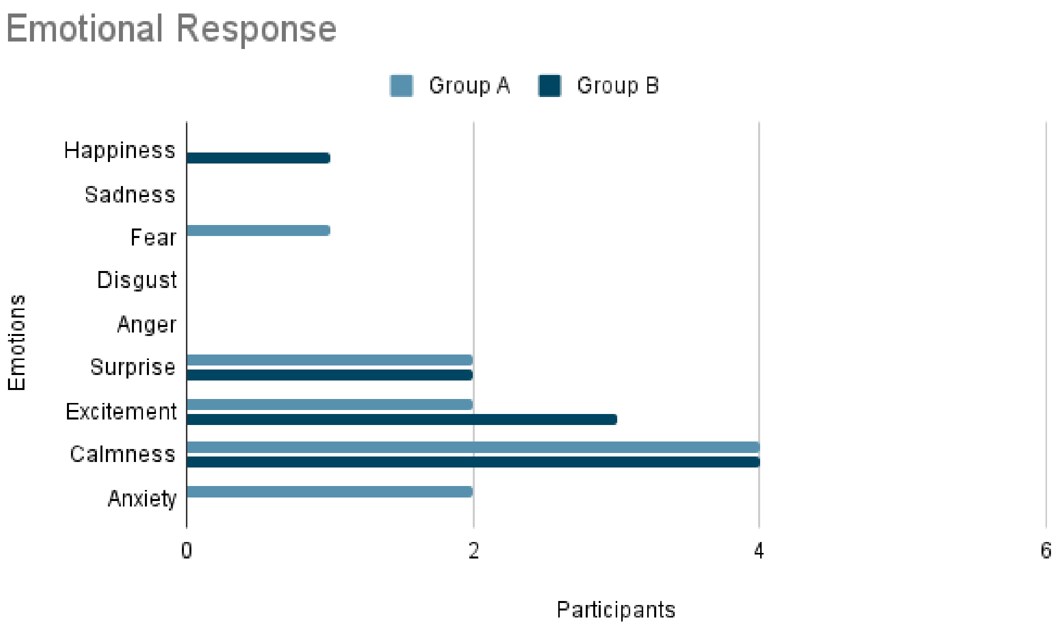


Figure 5.5: Distribution of different emotions in groups

Effectiveness of sensory feedback: The effectiveness of tactile feedback in contributing to the realism of the VR experience was rated by participants of group B with a mean score of 3.5, indicating that it was perceived as moderately effective. Similarly, the alignment of tactile sensations with the visual and auditory elements of the virtual environment was rated with a mean score of 3.5, indicating that the integration was generally successful, although there was scope for further improvement. In contrast, the contribution of the sound to engagement and immersion was rated more highly, with a mean of 4.17, which serves to highlight its significant impact on enhancing the overall experience. These findings indicate that while tactile feedback enhances the realism of the experience, sound plays a more significant role in fostering immersion and engagement. This suggests that future enhancements to tactile feedback could further improve its effectiveness.

5.3.2 Qualitative results

The qualitative feedback from both Group A and Group B participants provided valuable insights into the user experience, highlighting both successes and areas for improvement in the system. Group B, who experienced the full sensory feedback, responded positively to the immersive nature of the visual, auditory and tactile elements. Many participants commented that the coordination between audio and tactile sensations made the virtual world feel more tangible and engaging, transporting them into a mental space isolated from reality. This is in line with the aims set out in the Design chapter, where the integration of physical and auditory feedback was intended to enhance immersion.

However, some Group B participants pointed out certain sensory inconsistencies, such as the distracting noise of the virtual spheres, which detracted from the sense of immersion. There was also frustration with the lack of interactivity, particularly the inability to manipulate objects in the environment. While the sensory feedback was effective in enhancing the experience, these comments suggest that further refinement of the interactivity and sound design could create a more cohesive virtual world.

In contrast, participants in Group A, who did not receive tactile or auditory feedback, provided less detailed and enthusiastic responses. They appreciated the visual aesthetics of the experience, but their feedback focused more on technical issues such as glitches and motion sickness. Without the grounding effect of haptic feedback, participants were more aware of the limitations of the system, pointing to the need for improvements in stability and comfort.

Suggestions for improvement: In both groups, participants recommended strengthening the coordination between the sensory elements. In Group B there were suggestions to improve tactile feedback and make vibrations more pronounced, reduce distracting noise and improve interactivity with virtual objects. These suggestions are consistent with findings from previous research that emphasizes the importance of synchronizing sensory feedback to maintain immersion (as discussed in section 5.2).

5.4 Analysis and interpretation

The analysis and interpretation section examines the performance of the "Phantastic Sound Experience" system in relation to the hypotheses outlined at the beginning of the study. It begins by assessing the system's ability to meet key objectives, particularly in terms of improving immersion, presence, user satisfaction and reducing motion sickness through the use of multimodal sensory feedback.

This section also compares the results of this project with related work in the field, positioning the "Phantastic Sound Experience" within the broader context of VR research. By examining similarities and differences with other studies, the analysis highlights the unique contributions and advances made by this system, particularly in the integration of tactile and auditory feedback.

The final section considers the limitations encountered during the evaluation, such as the small sample size and technical limitations, which may have influenced the results. These limitations are considered alongside suggestions for refining the system, including improvements to sensory alignment and interactivity. By reflecting on these aspects, this section not only confirms the success of the system in achieving its primary objectives, but also sets the stage for future improvements.

5.4.1 Comparison with hypotheses

The evaluation of the "Phantastic Sound Experience" confirms the core hypotheses proposed at the beginning of the study. As discussed in the results, sensory feedback played a key role in enhancing the virtual reality experience.

Sensory feedback will increase the sense of presence:

Group B showed higher presence scores, confirming the hypothesis that multimodal feedback increases the user's sense of being in the virtual world. Sensory fidelity, driven by tactile and 3D audio cues, helped users feel more connected to the environment. This supports research by Witmer and Singer [90] which shows that sensory cues significantly improve the user's sense of presence. The close alignment of visual, auditory and haptic elements achieved this increase in presence, as predicted by the study design.

Sensory feedback will enhance immersion:

The data showed a significant improvement in immersion for Group B (with sensory feedback). The integration of 3D audio and tactile feedback successfully deepened participants' involvement, as evidenced by higher scores on questions related to immersion. This supports previous research emphasizing the role of sensory integration in creating a fully immersive VR environment. The tactile elements, synchronized with audio feedback, provided a multisensory experience that went beyond visual immersion alone. This was in line with the aims of the project and the findings of the literature reviewed earlier, in particular the work of Slater and Wilbur [68] which highlights that deeper immersion correlates with richer sensory input.

Sensory feedback can reduce motion sickness:

Lower reports of motion sickness in Group B supported the hypothesis that sensory feedback reduces discomfort. The tactile feedback likely provided participants with a greater sense of grounding and reduced disorientation, which helped to alleviate motion sickness. This finding is consistent with existing VR studies showing how sensory anchoring reduces cognitive dissonance and improves user comfort.

Sensory feedback has an impact on overall user satisfaction:

Group B participants expressed higher levels of satisfaction with the VR experience, consistent with the hypothesis that sensory feedback enhances the overall enjoyment and effectiveness of VR systems. In particular, tactile feedback was highlighted as an important factor in improving the realism and emotional engagement of the experience. In summary, the performance of the system largely confirmed the hypotheses, with sensory feedback playing a critical role in enhancing the user experience in terms of immersion, presence, motion sickness and satisfaction.

5.4.2 Comparison with related work

The results of the Evaluation of the project align with existing research on the role of sensory feedback in virtual reality, while contributing new insights into the specific effects of tactile and auditory feedback on user immersion, presence, and comfort.

Immersion and presence

Previous studies, such as those by Slater and Wilbur [68],and Hendrix and Barfield [37], emphasize the role of high visual fidelity and spatial audio in enhancing immersion and presence in VR. This study corroborates those findings, demonstrating that Group B, which experienced 3D audio and tactile feedback, reported significantly higher scores for immersion and presence than Group A, which lacked sensory feedback. These results reinforce the importance of sensory input in creating a deeply engaging virtual experience, echoing the findings of Dinh et al. [26], who found that multimodal sensory integration enhances the sense of presence.

multisensory integration

Research by McMahan et al. [52] highlights how tactile feedback enhances interaction and realism in VR environments. The "Phantastic Sound Experience" supports these conclusions, showing that Group B participants felt more connected to virtual objects through the tactile vibrations, which added an additional layer of realism missing in Group A. This indicates that haptic feedback, when well-synchronized with visual and auditory stimuli, significantly improves the user's overall experience and sense of presence.

Immersion and sensory feedback

In Eidenberger's Virtual Jumpcube, the integration of olfactory and tactile stimuli enhanced immersion by synchronizing non-audiovisual sensory inputs with visual cues [27]. This is consistent with the Phantastic Sound evaluation, where Group B, experiencing haptic feedback, showed higher immersion than Group A, underscoring the importance of coordinated sensory stimuli. On the other hand, Bruun-Pedersen et al. [15] explored the impact of multimodal feedback on perceived exertion during VR exercise. Although their results did not reveal significant changes in exertion, they highlighted the importance of sensory synchronization for realism, aligning with this study's finding that sensory feedback improves immersion.

Motion sickness and physical discomfort

Group B reported fewer symptoms of motion sickness than Group A, suggesting that grounding participants with tactile feedback helped alleviate discomfort and disorientation. This aligns with the conclusions of Dinh et al. [26] who observed that multimodal feedback reduces physical discomfort in VR. Both the Virtual Jumpcube and Phantastic Sound studies demonstrated that sensory feedback reduces motion sickness. Eidenberger noted that tactile stimuli helped minimize nausea by creating a more immersive experience [27]. Similarly, Group B participants in this study reported fewer motion sickness symptoms, confirming the hypothesis that haptic feedback reduces disorientation. In contrast, Bruun-Pedersen et al. focused more on exertion than motion sickness, though they acknowledged cybersickness challenges during pilot testing, emphasizing the need for careful sensory synchronization in reducing discomfort[15].

User experience and presence

Eidenberger's findings indicated that olfactory and tactile feedback significantly enhanced user excitement and enjoyment, a conclusion mirrored by the Phantastic Sound results, where Group B participants described the experience as more immersive due to multi-sensory engagement [27]. Bruun-Pedersen et al. found that sensory feedback increased participants' perception of realism in VR, even though the statistical differences were not strong. This qualitative feedback aligns with the Phantastic Sound evaluation, where tactile feedback enhanced the sense of being 'inside' the virtual environment [15].

Summary of findings

Both the Phantastic Sound and Virtual Jumpcube studies show that synchronized sensory feedback increases immersion, reinforcing the idea that multisensory input deepens the user's engagement with the virtual environment. In contrast, Bruun-Pedersen et al. found that while sensory feedback had less impact on perceived exertion, it still played a role in shaping the overall experience. Motion sickness was another key area where the Phantastic Sound and Virtual Jumpcube studies agreed, showing that sensory feedback helped to reduce discomfort and nausea. However, Bruun-Pedersen et al. focused primarily on exertional challenges rather than motion sickness. Despite these differences in focus, all three studies agreed that sensory feedback had a positive impact on the user experience, increasing satisfaction and presence, although the emphasis in each study varied between immersion and physical exertion [27, 15]. This comparison underscores the importance of integrating well-synchronized sensory feedback into VR experiences to maximize immersion, reduce discomfort, and enhance overall user satisfaction.

5.4.3 Limitations

While the evaluation provided valuable insights, several limitations should be acknowledged:

Sample size: The evaluation was conducted with a relatively small sample size (12 participants). While the results showed clear trends, the limited number of participants may have affected the generalizability of the findings. Future studies would benefit from a larger, more diverse pool of participants to increase the statistical power and reliability of the results.

Duration of interaction: Each participant spent only five minutes in the virtual world. Although this duration was chosen to avoid overstimulation and fatigue, it may not have been sufficient to fully capture the long-term effects of sensory feedback on user immersion, presence, or motion sickness. Longer exposure may provide more nuanced insights into how users adapt to and experience sensory feedback over time.

Technical limitations: The system's reliance on specific hardware (e.g., Vive Pro 2 for VR and vibration motors for haptic feedback) may have influenced the results. Differences in hardware configurations could alter the sensory experience, particularly in terms of audio quality and haptic feedback intensity. Future research could explore different hardware setups to see if these findings hold across platforms.

Limitations of interactivity: Several participants in Group B noted the lack of interaction with virtual objects, such as the inability to manipulate or throw the virtual spheres. This lack of interaction may have reduced overall immersion, even with the presence of sensory feedback. Addressing these interactivity limitations in future iterations of the system could lead to even greater engagement and a more fully immersive experience.

Trade-off between realism and performance: The visual and audio fidelity of the system was high, but this occasionally led to performance bottlenecks that could have affected the user experience. Although optimizations such as baking lighting were used, some participants still reported minor lag or visual glitches. Future work should focus on balancing high fidelity visuals with system performance to maintain immersion without introducing technical glitches.

In conclusion, while the evaluation provided strong support for the initial hypotheses, these limitations suggest areas for further refinement and exploration. Addressing these limitations in future studies will help to provide a more comprehensive understanding of the role of sensory feedback in VR and enhance the effectiveness of the "Phantastic Sound Experience" system.

5.5 Summary of findings

The evaluation of the "Phantastic Sound Experience" provided insights into the impact of sensory feedback, including 3D audio and tactile sensations, on user immersion, presence and satisfaction in a VR environment. The results confirm many of the initial hypotheses, while also highlighting areas for improvement in future iterations of the system.

Key findings from the evaluation include:

- **Presence:** The integration of multimodal sensory feedback, particularly tactile feedback, was instrumental in increasing the sense of presence. Group B participants felt more 'present' in the virtual environment, experiencing a stronger connection to the space, as indicated by higher scores on both quantitative and qualitative metrics. The seamless alignment of sound, touch and visuals helped create an immersive experience where participants felt they were truly "inside" the virtual world.

Immersion: The presence of tactile feedback and 3D audio significantly increased the overall level of immersion. Participants in Group B (with sensory feedback) reported higher levels of immersion compared to Group A. Sensory cues, such as vibrations synchronized with audio and visual elements, created a more convincing and immersive virtual environment, enabling users to engage more deeply with the VR experience.

Motion sickness: Group B experienced lower levels of motion sickness, likely due to the grounding effects of tactile feedback. By providing participants with physical cues that synchronized with their virtual actions, the system minimized disorientation, leading to a more comfortable experience. This suggests that sensory feedback may play a role in mitigating common VR problems such as dizziness and nausea.

Sensory feedback: Group B participants rated the effectiveness of sensory feedback highly, with particular praise for the integration of vibrations that matched visual and auditory events. However, there were still reports of slight discrepancies between sensory modalities, highlighting an area for refinement in future versions of the system.

User satisfaction: Overall satisfaction was higher in Group B, with participants noting the realism and emotional engagement provided by the sensory feedback. Tactile feedback in particular was seen as a critical element that contributed to the sense of realism and increased user enjoyment.

Overall, the "Phantastic Sound Experience" proved to be an effective and engaging virtual reality system, with the integration of tactile feedback and 3D audio greatly enhancing user immersion, presence and satisfaction. These findings provide a strong foundation for future research and improvements in multisensory VR experiences. By addressing the minor limitations and extending the successful elements of the current system, future iterations have the potential to provide even more immersive and compelling virtual environments.

5.6 Discussion

The analysis of immersion levels between Group A (without sensory feedback) and Group B (with sensory feedback) revealed some important, though modest, differences in how participants perceived their virtual reality experience. Group B, which experienced tactile vibrations synchronized with the audio feedback, reported slightly higher immersion, with an average mean score of 3.78 compared to 2.89 for Group A. While this result aligns with the hypothesis that multisensory feedback would enhance user engagement, the statistical analysis through t-tests showed that this difference was not consistently significant across all questions. The results of the t-test demonstrated significance in only one of the immersion questions. The question "To what extent did the virtual environment replace your real-world sensory experiences?" yielded a p-value of 0.02. This indicates that participants in Group B reported a greater sense of immersion in the virtual environment with regard to the replacement of real-world sensory input, which is likely attributable to Group A missing the auditive experience. However, no statistically significant differences were observed in the other questions related to immersion (e.g., p-values of 0.15 and 0.34 for the remaining questions). This lack of statistical significance necessitates a more cautious interpretation of the data, as it suggests that while Group B rated the experience as slightly more immersive, the difference may not be sufficiently pronounced to draw definitive conclusions.

Minor differences in immersion ratings:

Despite Group B consistently reporting higher scores across all immersion questions, the actual difference in ratings was relatively minor. To illustrate, the initial inquiry regarding immersion, "How would you rate your level of immersion in the virtual environment?," yielded mean scores of 4.0 for Group B and 3.33 for Group A. Similarly, the subsequent question concerning overall engagement exhibited means of 3.67 for Group B and 3.0 for Group A. These outcomes, while indicating that the participants in Group B perceived greater involvement in the virtual experience, demonstrate only moderate enhancements.

The third question was as follows: "To what extent did the virtual environment replace your actual sensory experiences in the real world?" (which yielded a significant p-value) is the most meaningful indicator of the potential benefits of sensory feedback. This may be attributed to the fact that the tactile vibrations facilitated a tangible connection between the participants and the virtual world, thereby enhancing the illusion that the VR environment had replaced their real-world surroundings. Nevertheless, the relatively modest effect sizes observed in the remaining immersion questions suggest that, on the whole, the sensory feedback had a somewhat limited impact on the participants' sense of immersion.

Insights from participant feedback:

The qualitative feedback from the participants lends support to the numerical data to a certain extent. A significant number of Group B participants observed that the synchronized audio and tactile vibrations enhanced their physical engagement with the virtual environment. Some participants even reported losing track of time, with responses such as, "I was fully absorbed into the virtual reality," and, "It could have been five seconds or two hours." These statements demonstrate how sensory feedback can facilitate immersion, thereby enhancing the engagement and disorientation of the experience in a positive manner.

In contrast, participants in Group A, who did not receive sensory feedback, were more conscious of their physical environment. Some also observed that the absence of tactile stimulation impeded their ability to fully immerse themselves in the experience. A number of participants observed that they remained conscious of external auditory stimuli and the passage of time, which is likely to have diminished their overall sense of immersion.

Limitations and potential explanations:

Regarding these findings, the low t-test values for the majority of questions highlight the necessity to contemplate potential constraints inherent to the study design. The study's statistical power is constrained by the relatively small sample size of six participants per group. A larger sample size would provide a more robust dataset, which could potentially reveal more significant differences between the groups. The low statistical power in this case renders it challenging to draw robust conclusions regarding the true impact of sensory feedback on immersion. A further potential limitation is the relatively brief exposure to the virtual reality experience, which lasted only a few minutes. It is possible that the effects of multisensory feedback, particularly those pertaining to the sense of touch, may require a longer period of interaction to become fully apparent. A longer exposure time may permit participants to become more fully immersed, which could result in more pronounced effects on both subjective immersion and presence. Furthermore, the calibration of sensory feedback may have been a contributing factor. Some participants in Group B indicated that the vibrations, although present, were not sufficiently intense to have a notable impact. This indicates that although the sensory feedback enhanced immersion to a certain degree, its potency or timing may have been inadequate to generate a genuinely immersive experience.

While the study provides some evidence that multisensory feedback, particularly tactile feedback, enhances immersion, the small effect sizes and lack of statistical significance in most questions indicate that the impact may be more modest than originally hypothesized. The one statistically significant result suggests that sensory feedback has the potential to replace real-world sensory input, but further research with larger sample sizes and more pronounced feedback mechanisms is needed to fully explore this effect. Future studies could improve the calibration of feedback and increase interaction times to allow for a deeper investigation into the role of multisensory inputs in enhancing immersion in VR environments.

CHAPTER 6

Conclusion and future work

6.1 Areas for improvement

Although the evaluation of the "Phantastic Sound Experience" was largely positive, several key areas for improvement were identified. One of the primary issues highlighted during the user tests was the occasional mismatch between sensory modalities, especially between the tactile feedback and the visual or auditory cues. While the vibrations contributed positively to immersion, inconsistencies in synchronization were noted. Participants felt that the vibrations were either too weak or out of sync with the visual stimuli, which reduced the overall sense of realism and presence. The quantitative results also indicated that while Group B reported higher levels of immersion and presence, the t-tests showed no significant difference between the two groups across most of the metrics. This suggests that while sensory feedback improved the experience for some users, the current system's implementation of haptic feedback did not lead to substantial improvements across the board. To address this, future development should focus on enhancing the precision and timing of the feedback, as well as exploring more dynamic and responsive feedback systems that can adjust in real-time to user interactions. Another area requiring attention is the intensity of the tactile feedback. Participants expressed a desire for more pronounced and varied vibrations, which would align better with the visual and auditory stimuli in the environment. As noted in the feedback, stronger tactile sensations would help users feel more physically present in the virtual world. By improving the haptic system to offer a wider range of tactile responses, the overall realism and interactivity of the system could be significantly enhanced. Finally, the small sample size (12 participants) limited the statistical significance of the findings. Although Group B's scores were consistently higher, the small sample may have prevented more conclusive results. Future studies should consider larger, more diverse participant groups to better assess the generalizability of the findings and gain deeper insights into how sensory feedback affects different types of users.

6.2 Implications for future work

The findings from this study provide a foundation for further exploration of sensory feedback in virtual reality environments. One key area for future research is the synchronization between sensory modalities, particularly between audio, visual, and tactile feedback. As participants in Group B reported that these elements were occasionally out of sync, improving synchronization could lead to a more cohesive and immersive experience. This could involve refining the system's latency, ensuring that vibrations occur precisely in tandem with visual and auditory stimuli. The emotional responses from participants, particularly their altered sense of time, suggest another interesting avenue for research. Group B participants, who experienced tactile feedback, often reported losing track of time during the virtual experience, indicating deeper immersion. Future research could explore the connection between time perception and sensory feedback, investigating how different combinations of sensory inputs (or their absence) affect users' sense of time within virtual environments. Moreover, further exploration of user comfort and the potential for sensory feedback to reduce motion sickness is necessary. Although Group B reported lower levels of motion sickness, the differences were not statistically significant. Future studies could focus on how varying the intensity, timing, or location of haptic feedback might improve comfort and reduce nausea during longer VR sessions. Exploring how sensory feedback can adapt dynamically based on user responses could also enhance comfort and immersion. Lastly, this research opens the door for more complex interactions between sensory modalities. Future systems could experiment with adaptive sensory feedback that responds not only to the virtual environment but also to user input, enhancing interactivity and presence. Additionally, investigating how individual differences—such as prior experience with VR or sensitivity to motion sickness—affect the perception of sensory feedback will provide insights into designing more personalized and effective VR experiences.

6.3 Conclusion

The "Phantastic Sound Experience" was designed with the primary aim of exploring how multisensory feedback, specifically 3D audio and tactile vibrations, impacts user immersion, presence, and satisfaction in virtual reality environments. The system was developed to address the research questions posed at the outset, focusing on how synchronized sensory modalities influence user experience. By allowing the participants to engage with synchronized haptic and auditory feedback, the system created an immersive experience that enabled the detailed evaluation of these sensory elements. The results confirmed that sensory feedback enhances the immersive experience. Group B, which experienced both auditory and tactile feedback, reported higher levels of immersion and presence compared to Group A, which experienced only visual and auditory feedback. While the increase in presence was modest, with no statistically significant difference found in the t-test results, the qualitative feedback indicated that the synchronized feedback contributed to a richer, more engaging experience. These findings are consistent with the works of Eidenberger and Bruun-Pedersen, who similarly explored the role of sensory modalities in VR but in different contexts. In comparison to Eidenberger's study, which highlighted olfactory and tactile integration, this project focused on auditory and tactile feedback, reaffirming the importance of multimodal integration for deeper engagement in virtual spaces. Bruun-Pedersen's research, while more focused on exertion, also highlighted how synchronized sensory feedback can increase the realism and user involvement in virtual environments, supporting the findings of this study. The system's design allowed for a focused investigation into how sensory feedback can enhance user immersion and presence. Although the differences in user-reported immersion and presence between the groups were not substantial enough to indicate statistical significance, they suggest that even slight enhancements in sensory feedback can positively affect the virtual experience. Moving forward, further refinements in the intensity and precision of feedback, as well as larger-scale studies, could better explore these subtle effects and provide more conclusive results.

In conclusion, the "Phantastic Sound Experience" offers insights into the role of multisensory feedback in virtual reality, contributing to a growing body of research in this area. The comparisons drawn with the works of Eidenberger and Bruun-Pedersen underscore the importance of carefully synchronizing sensory modalities to maximize immersion and presence. The findings from this study suggest that future research should explore even more sophisticated feedback mechanisms, such as adaptive sensory feedback that responds dynamically to user input, to further push the boundaries of immersive virtual reality experiences.

APPENDIX A

Questionnaires

Questionnaires: User Experience in Virtual Reality

Thank you for participating in this study. Please answer the following questions based on your experience with the virtual reality system. Your responses will help us evaluate and improve the VR experience.

Participant Information

1. Please enter your name: ______________________________

2. Please enter your age: ______________________________

3. Do you have experience with VR?
   Options: Yes / No

Presence

4. How strongly did you feel 'present' in the virtual environment during the experience?
   Options: Not at all present / Slightly present / Moderately present / Very present / Completely present

5. To what extent did you feel like you were 'inside' the virtual world rather than merely observing it?
   Options: Not at all / Slightly / Moderately / Very much / Completely

6. How aware were you of your actual physical surroundings while in the VR environment?
   Options: Not aware at all / Slightly aware / Moderately aware / Very aware / Completely aware

Immersion

7. How effectively did the virtual environment engage your senses?
   Options: Not effective at all / Slightly effective / Moderately effective / Very effective / Extremely effective

8. How would you rate your level of immersion while being in the virtual environment?
   Options: Not immersive at all / Slightly immersive / Moderately immersive / Very immersive / Completely immersive

9. How engaging did you find the VR experience overall?
   Options: Not engaging at all / Slightly engaging / Moderately engaging / Very engaging / Extremely engaging

10. To what degree did the virtual environment replace your real-world sensory experiences?
    Options: Not at all / Slightly / Moderately / Very much / Completely

11. Did you lose track of time while in the virtual environment? Please describe your experience.
    Open-ended response:

Motion Sickness

12. Did you experience any symptoms of motion sickness during the VR experience?
    Options: Yes / No

13. How would you rate the severity of your motion sickness symptoms during the VR experience?
    Options: None / Mild / Moderate / Severe / Extremely severe

14. If yes, please specify the symptoms you experienced.
    Options: Nausea / Dizziness / Headache / Disorientation / Other (please specify)

Emotional Response

15. How pleasant or unpleasant did you find the VR experience?
    Options: Very unpleasant / Slightly unpleasant / Neutral / Slightly pleasant / Very pleasant

16. How stimulating did you find the VR experience?
    Options: Not stimulating at all / Slightly stimulating / Moderately stimulating / Very stimulating / Extremely stimulating

17. How did the VR experience make you feel?
    Open-ended response:

18. Do you have a specific emotion that is connected to the VR experience?
    Open-ended response:

19. How intense were your emotional reactions during the VR experience?
    Options: Not intense at all / Slightly intense / Moderately intense / Very intense / Extremely intense

Sensory Feedback (Group B Only)

20. Rate the effectiveness of the tactile feedback (e.g., vibrations) in contributing to the realism of the VR experience.
    Options: Not effective at all / Slightly effective / Moderately effective / Very effective / Extremely effective

21. How well did the tactile sensations match what you saw and heard in the virtual environment?
    Options: Not at all / Slightly / Moderately / Very well / Perfectly

22. To what extent did the sound increase your engagement or immersion in the virtual environment?
    Options: Not at all / Slightly / Moderately / Very much / Completely

23. Were there any aspects of the sensory feedback that you found confusing or less intuitive?
    Open-ended response:

Feedback and Suggestions

24. What did you like most about the experience?
    Open-ended response:

25. What did you like least about the experience?
    Open-ended response:

26. Do you have any suggestions for improvement?
    Open-ended response:

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