EVALUATION OF PILOT PERFORMANCE IN A VIRTUAL REALITY (VR) BASED SIMULATED FLIGHT ENVIRONMENT

By

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Dedicated to my beloved little son, whose radiant presence has been the driving force behind this wonderful accomplishment.

Declaration

I, *Anam Pervaiz* declare that my MS thesis titled "**Evaluation of pilot in a virtual reality (VR) based simulated flight environment"** is my own work and has not been submitted previously by me for taking any degree from this University "National University of Sciences and Technology (NUST), Pakistan" or anywhere else in the country/world.

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Acknowledgment

Glory be to Allah (S.W.A), the Creator, the Sustainer of the Universe. He only has the power to honor whom He pleases, and to abase whom He pleases. Verily no one can do anything without His will. From the day I came to NUST till my departure, He was the only one Who blessed me, opened ways for me, and showed me the path to success. There is nothing that can pay back for His bounties throughout my research period to complete it successfully.

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Abstract

Flight simulation technology has become a vital tool for pilot training and performance evaluation, allowing aviators to refine their skills in controlled environments. This study compares pilot performance in two distinct simulation environments: Virtual Reality (VR) and traditional desktop-based flight simulators. The objective is to determine whether VR-based simulations offer advantages over desktop simulations regarding training effectiveness and pilot performance metrics. The research methodology involved recruiting 05 experienced pilots and subjecting them to a left-hand traffic pattern in two distinct flight scenarios (Clear and Adverse weather). Two types of comparisons were performed, i.e., test environment-wise (VR and Desktop) and scenario-wise (S1 and S2). During the experiment, objective performance metrics, i.e., altitude and heading deviation (Take-off, Crosswind, and Downwind), were collected and analyzed. Workload assessment was performed using the NASA TLX index, where the participants recorded their workload levels. Additionally, subjective evaluations from participants were gathered through a post-simulation questionnaire to capture their perceptions of realism, immersion, and overall training experience.

In Scenario 1, the difference between the participants' performance was not significant whereas, in Scenario 2, participants were **25.7%** better at maintaining their desired heading and **24%** better at maintaining their desired altitude in VR. These results suggest that participants generally performed better in maintaining their desired flight parameters, i.e., heading and altitude, in the VR environment compared to the desktop simulator, with more considerable improvements seen in Scenario 2. Subjective feedback depicts that VR offers enhanced situational awareness, improved flight performance, and a more immersive training environment. However, the NASA TLX score showed a more significant workload using VR hardware. These findings contribute to the ongoing discourse on the effectiveness of different simulation platforms in aviation training and highlight advantages and potential areas for improvement in VR-based flight simulation.

CHAPTER 1

INTRODUCTION

1.1 Background and Context

The evolution of flight simulators has been instrumental in shaping the training landscape for pilots and aviation personnel. These advanced tools serve as crucial aids in skill development, procedural training, emergency handling, and decision-making, enhancing overall flight proficiency and safety. The immersive nature of modern flight simulators provides an environment where pilots can confidently experiment with different scenarios, fine-tune their techniques, and master challenging maneuvers without the inherent dangers of live-flight practice. Furthermore, flight simulators have become indispensable tools in training new pilots, allowing them to acquire foundational skills before transitioning to actual aircraft. These simulations' comprehensive and dynamic nature facilitates learning and knowledge retention, nurturing a generation of competent and confident aviators. In addition to their instructional value, flight simulators play a vital role in ongoing pilot education and recurrent training. Experienced pilots can use these simulators to refresh their skills, encounter and mitigate challenging scenarios, and stay up-to-date with technological advancements in aviation. The continued advances in flight simulator technology promise even more realistic and sophisticated training experiences.

Flight simulation has become an integral tool for pilot training and performance evaluation in the aviation industry. In past years, desktop-based technologies have been used to create flight simulators, which offer pilots a computer-generated 3D environment where they can practice different flying scenarios. Virtual reality (VR), which provides a more immersive and realistic experience for pilots, has emerged as a possible substitute for conventional desktop-based simulators due to technological improvements.
As virtual reality (VR) technology matures, VR-based flight simulators are emerging as an exciting frontier, offering heightened immersion and a more profound sense of presence during simulated flights. In conclusion, the historical significance of proper training in aviation, coupled with the remarkable capabilities of modern flight simulators, underscores their vital role in pilot education and skill enhancement. Integrating virtual reality-based simulations further strengthens the effectiveness and impact of flight training, providing pilots with an unparalleled platform to prepare for the complexities and challenges of real-world flying. As the aviation industry evolves, flight simulators will remain essential in ensuring safe and proficient flight operations for pilots worldwide.

1.2 Problem Statement

There is a growing interest in emerging technology, ‘Virtual Reality’ (VR), because of technological developments, improved accessibility, and a wider variety of applications. It appeals to a broad spectrum of people because it provides immersive and engaging experiences that traditional applications cannot match. Among the diverse applications of VR, using this technology in flight simulation has caught a lot of attention. While some studies have investigated the benefits of VR in other domains, there is a need for comprehensive research specifically focused on the comparison of pilot performance between VR flight simulators and desktop-based simulators. This research aims to bridge the gap in existing knowledge and provide valuable insights for flight training programs and simulator developers. Studying the usability of VR-based flight simulations and estimating pilot performance in emergency/critical scenarios is necessary.

Moreover, the linkage between pilot handling qualities and dynamic conditions is an exciting area where VR-assisted flight simulation setups can help. During the literature review phase, it was observed that most existing studies focus on conventional flight simulators. VR-based flight simulation studies are rare. In the current studies, pilot performance is evaluated in normal flying scenarios. At the same time, there is little focus on the dynamic flight environment and its effect on pilots' flight path and performance. These identified gaps in existing research served as a motivation to select and pursue the subject research topic.

1.3 Research Objectives

The primary objective of this thesis is to compare pilot performance between virtual reality flight simulators and desktop-based simulators. The specific research objectives include:

1. To evaluate virtual reality flight simulators' functional fidelity and realism compared to desktop-based simulators.
2. To examine the effects of virtual reality on pilot performance metrics based on flight data and to assess the workload in a dynamic flight environment.
3. To identify potential limitations or challenges associated with adopting virtual reality flight simulators.

1.4 Significance

This study is important as it advances knowledge of the advantages and disadvantages of virtual reality flight simulators compared to desktop-based simulators. The findings of this research will be valuable in improving flight training programs, simulator development, and aviation regulatory bodies. The knowledge acquired from this study can help decision-makers choose and use flight simulation technology more effectively, thereby enhancing pilot training and increasing flight safety. The rationale for carrying out this research is as follows:

To be used in experiments: The system will be used in research-based projects like studying the pilot performance in routine and dynamic scenarios and the effects of input parameters on flying qualities.

To be used in Aviation setups: As a pilot, performance is the key contributor in aviation. Well-trained and competent military pilots can defend their airspace against their adversaries. In civil aviation setup, pilots with good expertise will also have safe flights and fewer flight accidents, thus saving the national exchequer. The selected research topic is highly significant to national interests based on the above-stated relevance.

Cost Effective: Commercially available flight simulators are costly. The research is focused on designing a low-cost flight simulation setup and performing requisite training and assessments.

Advanced simulation software: The VR hardware is integrated with an advanced flight simulator like Xplane12 to provide additional software capabilities and a user-friendly interface.

1.5 Scope

This thesis compares pilot performance between virtual reality flight and desktop-based simulators. The study will primarily consider performance metrics related to flight handling, precision, and amount of workload. However, it is essential to acknowledge that the scope of this study may not encompass all aspects of pilot performance or simulator evaluation. Additionally, limitations related to sample size, simulator configurations, and environmental setup may affect the generalizability of the findings.

1.6 Organization of the thesis

This thesis is structured into five chapters. Chapter 1 introduces the research topic, outlining the background, problem statement, objectives, research questions, significance, scope, and limitations. Chapter 2 reviews relevant literature on flight simulators, virtual reality, and pilot performance evaluation. Chapter 3 presents the methodology employed for data collection and analysis. Chapter 4 presents the findings and analysis of the study. Finally, Chapter 5 summarizes the study, conclusions, and recommendations for future research. By comparing pilot performance in virtual reality flight simulators and desktop-based simulators, this study seeks to provide evidence-based insights that will contribute to the ongoing development and implementation of flight simulation technologies, ultimately enhancing pilot training and flight safety.

CHAPTER 2

LITERATURE REVIEW

2.1 Flight Simulators

2.1.1 History of Flight Simulators

Since the earliest days of human flight, the significance of thorough training has been widely acknowledged. The mythological tale of Icarus and Daedalus, often interpreted as a warning against flying too close to the sun, can also be understood as a cautionary lesson about the importance of proper training and familiarization with aircraft controls and performance before attempting daring aerial feats. This historical understanding emphasizes the need for skill and competence in piloting before embarking on complex and high-flying endeavors. In the contemporary world of aviation, a flight simulator stands as a sophisticated device or software that faithfully recreates the experience of piloting an aircraft. By meticulously simulating an aircraft's physics, controls, and behavior and integrating computer-generated graphics, audio, and physical motion, flight simulators offer pilots and aviation professionals an invaluable platform to practice and refine their skills within a remarkably realistic flight environment. Flight simulators offer compelling advantages, as they present a safe and cost-effective alternative to actual flight training, effectively reducing risks and expenses associated with real-flight operations.

The roots of flight simulation trace back to the early 20th century, coinciding with the advent of manned flight. During this period, the concept of flight simulators emerged to provide flight training to aspiring pilots. Initially, rudimentary training involved using low-powered machines, allowing trainees to practice fundamental flight controls, such as taxiing skills. To develop more comprehensive piloting abilities, trainees required exposure to aileron and elevator controls, which were facilitated by implementing higher-powered machines. These advanced devices boasted enhanced fidelity, offering more effective training experiences [1]. Early endeavors towards creating comprehensive ground-based simulators were inspired by grounded aircraft that still retained their capacity to react to aerodynamic forces. One such device was the "Sanders Teacher," an exposed plane mounted on a universal joint and oriented to face the direction of the wind as shown in Figure 1. It responded to inputs from the elevator, aileron, and rudder controls, allowing trainees to practice and refine their piloting skills.

In contrast to the "Sanders Teacher," another notable simulator was "The Billings Trainer." This simulator featured wings attached to a control column and rudder bar, enabling rotation and alignment with the wind. Devices like these were commonly referred to as motion bases and saw significant development during World War I.

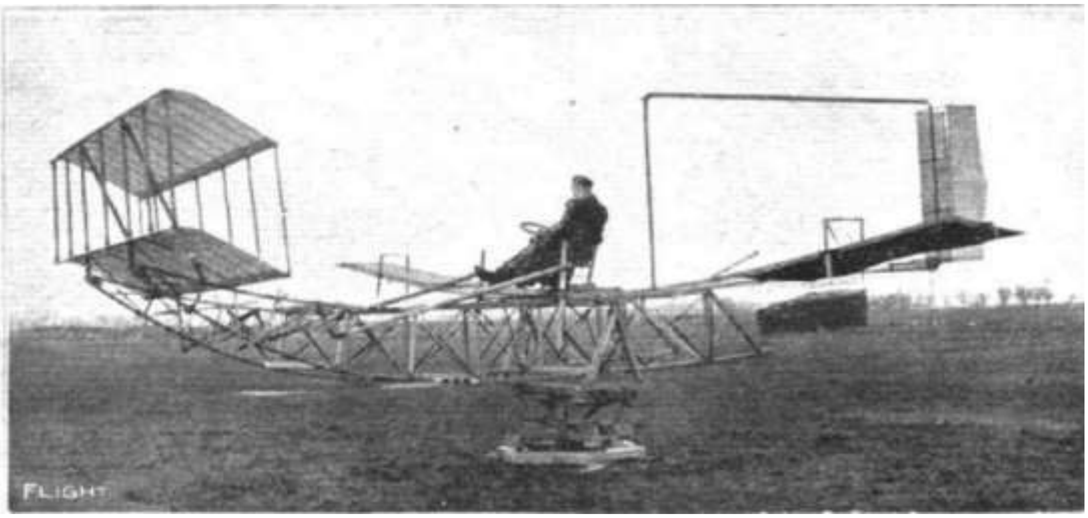

Figure 1: Sanders Teacher

With technological advancement, the trend shifted toward developing more sophisticated and higher-fidelity flight simulators. Many developers made many contributions, but the “Link Trainer” created by American aviator and inventor Edwin Link was a breakthrough in flight simulation as shown in Figure 2. It became the most popular and successful flight simulation device in that era. Early in the 1930s, Links' flying school started teaching instrument flying [2]. The Link Trainer had complete flight controls and instruments, including an artificial horizon essential for instrument flying. Flight movements (pitch, roll, yaw) were built around pneumatics. Flight instructors could observe a student operating the Link Trainer's flight controls via an external repeater. The first airline that used the developed Link Trainer for pilot training was American Airlines in 1937. The Link Trainer was created in a variety of versions and distributed throughout the world.

The relentless progress of technology ushered in a paradigm shift in the development of flight simulators, leading to the creation of more intricate and high-fidelity systems. While numerous developers made noteworthy contributions to this field, one particular innovation emerged as a transformative landmark - the "Link Trainer," devised by the accomplished American aviator and inventor Edwin Link. This apparatus garnered unparalleled popularity and success as a flight simulation device. In the early 1930s, Edwin Link's flying school took a momentous step by introducing instruction in instrument flying. The Link Trainer was distinguished by its comprehensive flight controls and instruments, featuring a critical artificial horizon indispensable for honing instrument-based flying techniques. The simulator's sophisticated flight movements, encompassing pitch, roll, and yaw, were ingeniously orchestrated through pneumatic principles. Flight instructors could closely monitor students' utilization of the Link Trainer's flight controls via an external repeater system, facilitating effective guidance and performance evaluation [4]. A significant milestone in flight training occurred when American Airlines became the pioneering airline to integrate the Link Trainer into its pilot training program in 1937. This heralded a new era of flight simulation in the aviation industry. Subsequently, the Link Trainer underwent multiple iterations and versions, achieving widespread distribution and adoption on a global scale. In doing so, it solidified its position as a pioneering and influential force that significantly shaped the landscape of flight simulation.

Figure 2: Link Trainer

From the 1940s to 1950s, analog computers were developed and used for solving aircraft equations of motion. These computers could respond to aerodynamic forces and significantly contribute to flight simulation in that era. The limitation at that time was the non-availability of accurate flight parameters data. This situation changed drastically upon the availability of extensive flight data as several type-specific flight simulators were developed with enhanced features during the 1940s [3]. Another development was done by Link based on the requirement given to him by the British to enhance the skills of celestial navigation as shown in Figure 3. This requirement was fulfilled by a trainer developed by him with the help of a navigation expert. It had an aimer station setup housed in a large building used by the bomber crew. The pilots performed the flying while navigation aid was provided by the crew using radio aids included in the station.

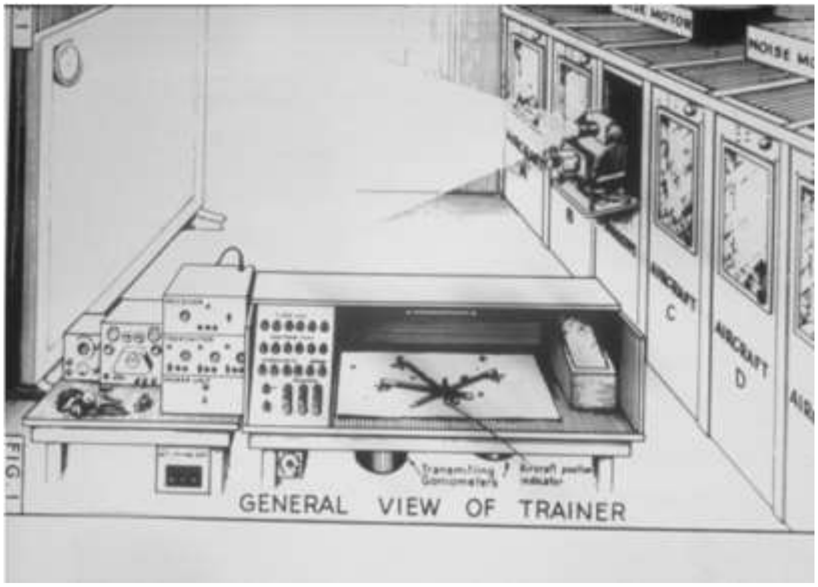

Figure 3: First Celestial trainer

In the early 1960s, Link made a groundbreaking advancement in flight simulation by developing the specialized digital computer known as the 'Link Mark I.' This innovation enabled real-time simulation, significantly enhancing the accuracy and responsiveness of flight simulators. Before the mid-1950s, most simulators lacked motion capabilities and were fixed base, limiting their realism. In 1969, the Faculty of Mechanical Engineering at Delft University of Technology introduced the first 3 DOF motion systems (roll, pitch, heave), utilizing hydraulic actuators with hydrostatic bearings. This motion system provided a more dynamic and immersive flight experience for pilots, replicating key movements of an aircraft during flight. With the advent of faster and more powerful general-purpose computers by the 1970s, real-time simulation became even more feasible, enabling flight simulators to deliver more accurate and responsive training scenarios. Subsequently, in 1977, the first commercially available motion system having six degrees of freedom (6 DOF) was introduced (as shown in Figure 4), incorporating pitch, roll, yaw, surge, sway, and argued movements. This advancement further elevated the realism of flight simulation, approaching a level of fidelity that mirrored actual flight conditions.

Figure 4 : First 6 DOF motion system

Flight simulation has a rich history dating back to its inception pertaining to visual cues with various projection techniques used to generate flight scenery, and several techniques were introduced, such as film projection, point-light source projection, and Closed Circuit Television (CCTV) systems. The General Electric Company was pivotal in advancing flight simulation by introducing the first computer-generated image (CGI) systems for space programs. Initial versions started with producing 2D-based 'pattern ground plane' images and later evolved to real-time production of three-dimensional (3D) images for a more immersive experience. Today, the continuous technological advancements in CGI systems have led to remarkable speed, performance, and fidelity improvements. These advancements have resulted in high-quality visuals and real-time updating rates, further enhancing the realism and effectiveness of flight simulators. The cumulative effect of these developments has significantly elevated the fidelity and utility of flight simulators, garnering recognition and authorization from the Federal Aviation Administration (FAA) for their use in simulator training within the aviation industry. These advancements have revolutionized pilot training, providing a safe, cost-effective, and highly realistic platform for aspiring pilots and aviation professionals to hone their skills and enhance their expertise.

1981 marked a significant turning point in the democratization of flight simulators when IBM introduced the personal computer (PC) as shown in Figure 5, granting individual general aviation pilots access to these sophisticated simulations. In their initial incarnation, these PC flight simulation programs were presented as desktop-based games employing simple keyboard controls. However, technological advancements propelled developers to engineer flight control hardware, encompassing control yokes, rudder pedals, and throttles, thus enhancing the immersive and realistic flight experience. In the contemporary landscape, various flight simulation software options emerged over time. These software packages have garnered considerable acclaim for their meticulous aircraft instrumentation modeling, accurate representation of flight dynamics, and realistic depiction of external scenery. By harnessing robust graphic models, these simulators effectively replicate the sensations and intricacies of actual flight experiences. For aspiring pilots and student aviators, Personal Computer Aviation Training Devices (PCATDs) present a cost-effective and readily accessible means to engage in simulated flights for educational purposes. The Federal Aviation Administration (FAA) has duly recognized the effectiveness of PCATDs and now acknowledges them as a valid method for obtaining instrument flight training.

Consequently, up to ten hours of PCATD training may be credited to substitute for aircraft flight time in instrument rating training, provided it is conducted under the competent guidance of an authorized instructor. In summary, the introduction of the personal computer in 1981 revolutionized the accessibility of flight simulators, enabling individual pilots to experience the virtual skies. Ongoing technological advancements and the diverse range of flight simulation software available today continue to uphold the industry's reputation for precise aircraft modeling and immersive flight experiences. The integration of flight control hardware and the acceptance of PCATDs by the FAA has further solidified the significance of flight simulation in aviation training and education.

Figure 5: IBM’s First Computer

The genesis of VR-based flight simulation devices can be historically attributed to Ivan Sutherland's groundbreaking concept of the "Ultimate Display" in the 1960s. Sutherland envisaged a visual interface that surpassed conventional screens, acting as a transformative portal to a virtual realm wherein users could encounter an immersive, interactive, and real-time experience. Notwithstanding, the feasibility and cost-effectiveness of VR flight simulation were constrained by prevailing constraints in hardware and software, impeding its practical implementation for an extended period. However, the advent of pioneering devices like the Oculus Rift and HTC VIVE precipitated novel prospects for VR-based simulation. In parallel, advancements in technology and software platforms, exemplified by X-Plane 12, AeroFly2, and Microsoft Flight Simulator, have amplified the potential for developing and deploying more intricate flight simulators, augmenting realism and complexity in the virtual flight domain.

2.1.2 Types of Flight Simulators

Different ground training devices are mainly categorized into three types based on FAA categorization, i.e., full flight simulators, flight training devices, and aviation training devices [6].

2.1.2.1 Full Flight Simulator

The first flight simulator category is the Full Flight Simulator (FFS), an instrumentality designed to present a realistic flight experience, encompassing a meticulous replication of the aircraft's cockpit and dynamic motion. Predominantly deployed for the training of commercial pilots, FFS stands as the most financially demanding variant of flight simulators, as it integrates exceedingly sensitive hydraulics along with comprehensive visual display systems. These FFS units are stratified into four discrete levels, designated as Level A through Level D. Level A FFSs possess a motion platform operating along three axes of movement (3 DOF) with an elementary visual interface. Level B FFSs extend these capabilities by retaining 3-axis motion attributes while augmenting the simulation with night-time visual representations and a more intricate aerodynamic model exhibiting heightened fidelity. Level C FFSs emerge with an advanced 6-degree-of-freedom (6 DOF) motion system as shown in Figure 6, rendering motion along six independent axes, accompanied by both day and night visual displays and a horizontal field of view (FOV) spanning 75 degrees per pilot, compounded by a dynamic control loading mechanism. At the apogee of sophistication, Level D FFSs are distinguished by their fully-fledged 6 DOF motion platform, affording unparalleled realism in flight dynamics, complemented by an expansive 150-degree FOV for each pilot, augmented visual fidelity during all weather conditions, and the inclusion of dynamic control loading functionality, thereby ensuring the utmost fidelity in pilot training. Owing to their elevated operational and developmental costs, the deployment of FFSs is customarily constrained to the domain of professional pilot training programs, where their apparent advantages and requisite reliability justify the considerable investment.

Figure 6: Full motion simulator

2.1.2.2 Flight Training Device

The second category of flight simulators is referred to as Flight Training Devices (FTDs) as shown in Figure 7. These devices encompass various qualification levels, and their design entails an enclosed cockpit along with visual cues specifically tailored to replicate the characteristics of a particular aircraft type. Unlike Full

Flight Simulators (FFS), FTDs may not always include a motion system. Still, they can facilitate training and confer certifications for commercial and airline pilot flight training.

FTDs find extensive use in aviation training institutes and the airline industry, serving as essential tools for training new recruits, promoting personnel to higher ranks, and facilitating aircraft conversion training. They effectively bridge the gap between theoretical instruction and actual flight experience, providing trainee pilots hands-on practice in a simulated yet immersive environment. These training devices are further classified into Levels 1 through 7, with Levels 1 to 3 historically assigned to older devices, which are no longer in use and have been deemed obsolete. The prevailing categories, Levels 4, 5, and 6, primarily cater to fixed-wing devices, accommodating training requirements for various types of fixed-wing aircraft. Conversely, Level 7 pertains to rotary-wing devices, catering exclusively to helicopter training needs. FTDs are indispensable for honing essential aviation skills, ensuring safety, and enhancing the competence of aspiring pilots and experienced aviators seeking to refine their proficiencies in specific aircraft types. FTDs play a pivotal role in nurturing a new generation of skilled and adept pilots within the aviation industry through their systematic and pragmatic approach to flight training.

Figure 7: Flight Training Device (FTD)

2.1.2.3 Aviation Training Device

The third type of training device employed in aviation is the Aviation Training Device (ATD), with the Personal Computer Aviation Training Devices (PCATDs) falling under this category as shown in Figure 8. ATDs are characterized by their relatively simplistic design, typically comprising an aircraft control console equipped with flight controls necessary for practicing flight maneuvers, a personal computer for computational purposes, and monitor screens to display visual simulations.

ATDs are categorized into two main types: the Basic Aviation Training Device (BATD) and the Advanced Aviation Training Device (AATD). The BATD represents the entry-level variant, while the AATD is a more sophisticated version, incorporating additional advanced features.

The AATD distinguishes itself by offering enhanced capabilities such as an avionics display console, a cockpit symbology designed to faithfully replicate that of an actual aircraft, and comprehensive simulations of flight performance and aircraft control parameters, encompassing pitch, bank, and yaw. These features contribute to a more immersive and realistic training experience for aspiring pilots, allowing them to practice and refine their skills in a simulated environment that closely mirrors real-world conditions.

Figure 8: Aviation training device (ATD)

2.1.3 Applications of Flight Simulator

Flight simulators serve diverse applications, including:

Pilot Training: Flight simulators play a pivotal role in comprehensive pilot training programs, facilitating the instruction of pilots in handling dynamic flight scenarios, mastering emergency procedures, and improving proficiency in executing intricate flight maneuvers [5]. They offer a safe and controlled environment for trainees to develop essential skills and gain experience before engaging in actual flights, contributing significantly to flight safety and competence.

Aircraft Design and Testing: Flight simulators assume a crucial role during the aircraft design and testing phase, enabling engineers and designers to evaluate the aerodynamics of aircraft designs and assess their performance under various weather and environmental conditions. These simulations aid in identifying potential issues, optimizing designs, and ensuring that the aircraft meets regulatory and safety standards before physical prototypes are constructed and tested.

Research and Development: Flight simulators are valuable tools in the realm of research and development, providing a means to simulate real-world flight conditions and investigate complex aviation phenomena. Researchers utilize simulators to study human factors in aviation, explore pilot behavior, and develop innovative technologies and techniques to enhance flight safety, efficiency, and overall aviation performance.

Entertainment: Beyond their utilitarian applications, flight simulators offer recreational enjoyment to enthusiasts through gaming platforms, virtual reality experiences, and amusement park rides. These entertainment-focused simulators allow individuals to experience the thrill of flying and piloting aircraft in simulated environments, appealing to aviation enthusiasts and the general public.

In summary, flight simulators occupy a central position in the aviation industry, serving as indispensable instruments for pilot training, aircraft design and testing, research endeavors, and recreational pursuits. Their versatility, cost-effectiveness, and capacity to provide safe and controlled training environments have made them vital in advancing aviation knowledge, safety, and innovation.

2.2 Basics of Virtual Reality

2.2.1 The Technology

Virtual reality (VR) is a cutting-edge technology that simulates a realistic and immersive three-dimensional computer-generated environment designed to be experienced by users through specialized VR headsets or similar devices. The virtual environment can be interactive, allowing users to move within the digital space, manipulate objects, and explore virtual realms. This engenders a profound sense of presence, making users feel as if they are physically present in the simulated world. VR technology's core components include hardware and software elements [7]. The hardware includes the VR headset, a display screen for each eye to create stereoscopic visuals and sensors that track the user's movements. The latter feature, known as positional tracking, ensures that the virtual world responds to the user's actions and orientation, enhancing the sense of realism and immersion.

On the other hand, the software component of VR is responsible for generating and rendering the virtual environment. This includes creating interactive experiences, designing captivating games, and simulating various scenarios and situations. The software plays a pivotal role in producing engaging and lifelike simulations that form the backbone of the VR experience.

The applications of VR technology are diverse and span numerous fields. In the realm of entertainment, VR has revolutionized gaming, providing players with deeply immersive and interactive experiences. Furthermore, VR enables virtual travel and tourism, allowing individuals to explore distant locations from the comfort of their homes. Beyond entertainment, VR finds extensive use in education and training. It facilitates experiential learning, offering students hands-on experiences in diverse subjects like science, history, and art. In the realm of professional training, VR simulations are deployed to train individuals in complex and hazardous environments, including medical procedures, industrial operations, and military scenarios [8]. Moreover, VR technology serves therapeutic purposes, as it can be employed in exposure therapy to treat anxiety disorders and phobias. It allows individuals to confront their fears in a safe and controlled environment, aiding in desensitization.

Though VR has been around for several decades, recent advancements in hardware and software have led to greater accessibility and affordability for consumers. This has resulted in a surge in VR adoption and popularity, and the technology is projected to witness continuous growth and innovation in the foreseeable future. As the VR ecosystem evolves and expands, its potential for transformative applications in various domains will continue to captivate the imagination of users and industries alike.

2.2.2 Types of Virtual Reality

Virtual reality can be classified into five types which are explained in following subsections: -

2.2.2.1 Fully immersive

A fully immersive virtual reality (VR) experience denotes an intricate and comprehensive experience in which users are entirely occupied within a simulated environment, necessitating the implementation of specialized hardware and software components to achieve a heightened sense of presence and authenticity. A combination of sophisticated equipment is employed to create such a profound level of immersion. A head-mounted display (HMD) is a fundamental element, securely worn on the user's head and equipped with high-resolution displays for each eye, facilitating stereoscopic visuals. Stereo audio effects are incorporated to produce spatial sound, further enhancing the illusion of being physically situated within the virtual world. Alternatively, a Cave Automatic Virtual Environment (CAVE) system may be utilized, featuring multiple screens surrounding the user to project high-quality visuals, offering a more expansive and all-encompassing VR experience. Accurate and seamless tracking of user movements is crucial for a fully immersive encounter. Sensory gloves and tracking controllers are deployed to precisely monitor the trajectory of hand and head motions, enabling natural interaction with virtual objects and seamless manipulation of the digital environment. Furthermore, high-performance computing hardware ensures a smooth and responsive VR experience. Powerful graphics processing units (GPUs) and central processing units (CPUs) effectively render and process complex visual scenes in real-time, augmenting the overall sense of realism.

Fully immersive VR experiences have gathered significant attention and application in diverse domains. In the gaming and entertainment industries, they offer players an unparalleled level of engagement, interactivity, and emotional immersion. Users can traverse vast virtual worlds, interact with lifelike characters and objects, and partake in intricate gameplay, culminating in an exceptionally captivating and gratifying gaming experience. Moreover, the educational sector has embraced fully immersive VR experiences for training purposes, recognizing their potential to revolutionize learning. Virtual reality facilitates experiential learning, enabling students to explore historical events, embark on virtual excursions to distant locations, conduct simulated scientific experiments, and participate in immersive educational simulations. Such immersive and interactive educational experiences foster deeper comprehension and retention of academic content. As VR technology progresses and becomes more accessible, fully immersive VR experiences are poised to make significant strides across various industries. The ability to transport users to alternate realities, evoke emotions, and facilitate experiential learning is reshaping how digital content is encountered and consumed, offering promising prospects for the future of VR applications.

2.2.2.2 Non-immersive

Non-immersive virtual reality refers to a VR experience achieved through a computer interface, enabling users to interact with virtual environments and manipulate characters and activities using computer software. However, the degree of interactivity and immersion within these created environments is limited or minimal. An illustrative example of non-immersive VR is found in video games, where players assume control over avatars within the game that possess unique characteristics, animations, and abilities. While users can influence the actions of their avatars, the level of immersion and responsiveness from the virtual environment is restricted, as the virtual world does not fully interact with the user compellingly. Similarly, Computer-Aided Design (CAD) modeling software for creating three-dimensional content is another instance of non-immersive VR. Users can construct and manipulate digital objects in a virtual environment, yet the simulated world does not provide extensive interaction or feedback to the user. These scenarios focus on designing and visualizing the objects rather than immersing the user in a lifelike and interactive virtual world.

In non-immersive VR experiences, users remain aware of the physical reality surrounding them and do not experience a sense of presence or full immersion within the virtual environment. The level of interaction and responsiveness from the virtual world may be limited to the actions dictated by the user through the computer interface, without engaging in realistic interactions or generating a profound sense of being part of the digital environment. Nonetheless, non-immersive VR technologies serve valuable purposes, such as providing entertainment and enabling creative design processes. As advancements in VR technology continue, the boundaries between immersive and non-immersive experiences may blur, leading to more comprehensive and interactive virtual experiences that merge aspects of both realms.

2.2.2.3 Semi-immersive

Semi-immersive virtual experiences encompass a technology that offers users a partially virtual environment, giving them the perception of being immersed in a different reality while remaining aware of their physical surroundings. This intermediate level of immersion strikes a balance between complete immersion and full awareness of the real world. Through semi-immersive VR, users can focus on the digital imagery and experience a sense of presence within the virtual environment. The technology leverages high-quality 3D graphics and realistic sound effects to create a compelling and engaging experience. However, unlike fully immersive VR, users in a semi-immersive setting can easily switch their attention back to the physical world and maintain awareness of their surroundings.

Semi-immersive technology is frequently employed in educational and training contexts, where it offers a practical solution for simulating various scenarios and environments. Educational applications utilize high-resolution displays, powerful computing systems, and sometimes projectors or hard simulators that partially replicate the design and functionality of real-world mechanisms. These elements contribute to a more authentic and immersive learning experience, enabling students to explore complex concepts and engage in interactive simulations. Training applications leverage semi-immersive VR to prepare individuals for real-world scenarios without exposing them to potential risks. For example, flight simulators used in pilot training often fall into this category, providing trainee pilots with a realistic cockpit environment and flight dynamics while maintaining the ability to exit the simulation at any time safely.

Semi-immersive VR technology caters to various industries, bridging the gap between fully immersive experiences and traditional non-immersive interactions. Its ability to balance realism and real-world awareness makes it a valuable tool for training, education, and other applications that benefit from a mix of virtual and physical environments. As technology advances, the boundaries between these VR categories may evolve, enhancing the possibilities for seamless and interactive virtual experiences.

2.2.2.4 Collaborative

Collaborative Virtual Reality (VR) is a form of VR that enables users from different geographical locations to converge in a shared virtual environment as 3D animated characters. This technology fosters real-time interaction and collaboration among users, allowing them to engage with each other's virtual personas within the virtual space. A notable example of Collaborative VR can be observed in certain mobile games like Player Unknown's Battlegrounds (PUBG), where players assume the roles of virtual 3D characters and join forces or compete against each other in a shared virtual environment. In this context, players from diverse locations can participate simultaneously, forming teams, communicating, and collaborating to achieve common goals or engage in competitive gameplay.

While Collaborative VR environments promote interactive experiences and enable users to interact with each other's virtual representations, they may not be fully immersive. Unlike fully immersive VR experiences that aim to transport users entirely into an alternate reality, Collaborative VR maintains a level of awareness of the user's actual physical surroundings. In Collaborative VR, users experience a sense of presence within the shared virtual environment. Still, they can easily transition their attention back to the real world and interact with the physical environment when necessary. This characteristic distinguishes Collaborative VR from fully immersive VR, where users are fully enveloped within the digital realm and may not be as aware of their physical surroundings.

Collaborative VR environments hold significant potential for fostering social interactions, teamwork, and shared experiences across distances. They facilitate cross-border collaborations, virtual meetings, and shared training experiences, enhancing communication and cooperation among users regardless of their physical locations. As technology evolves, Collaborative VR will likely play an increasingly pivotal role in bridging geographical barriers and enabling shared virtual experiences.

2.2.2.5 Augmented Reality

Augmented Reality (AR) represents a fusion of the physical world with virtually generated environments, blending auditory, visual, and other sensory information from the virtual realm to enrich the perception of the real world. By superimposing computer-generated graphics onto the real-world environment, AR leverages various computer vision techniques to achieve this integration, enabling multiple applications such as navigation assistance, mechanical maintenance support, and social interaction enhancements. Nonetheless, AR encounters several challenges, including precise tracking of real-world elements, accurate alignment of virtual objects, appropriate illumination considerations, and seamless overlaying of virtual features onto the physical environment.

Augmented reality and virtual reality differ significantly in their nature of experience, level of immersion, real-world interaction, and hardware requirements. While AR maintains a partial immersion with real-world awareness and allows interaction with the physical environment, VR provides a fully immersive virtual experience, isolating users from the real world as shown in Figure 9. AR applications often utilize smartphones, tablets, or AR glasses, while VR typically requires specialized head-mounted displays (HMDs). These distinctions in technology and user experience make AR and VR distinct but complementary technologies, each offering unique benefits in various domains. The differences between AR and VR are listed in Table 1:

Feature	**Augmented Reality**	**Virtual Reality**
Nature of Experience	Blends real and virtual elements	Fully immersive virtual experience
Real-world Interaction	Interacts with physical surroundings	Isolated from the physical world
Level of Immersion	Partial immersion with real-world awareness	Complete immersion with limited real-world awareness
Hardware Requirements	Generally utilizes smartphones, tablets, or glasses	Typically involves head-mounted displays (HMDs)
Applications	Navigation, maintenance support, social interaction	Gaming, training, simulation, virtual experiences

Table 1: Difference between AR and VR

Figure 9: VR vs. AR

2.2.3 Levels of VR immersion

Immersion is a cognitive state characterized by partial or complete absorption in a particular experimental setup. This psychological phenomenon is discerned by a heightened sensation of presence or being confined "in the moment" or "in the zone." When an individual is completely engrossed in an endeavor, he exhibits increased focus, attention, and emotional involvement while losing track of time and the outside world. Within virtual reality (VR) purview, immersion delineates the degree to which a user experiences a profound engagement and authentic presence within the simulated environment [9]. It necessitates the development of a VR simulation that manifests a high degree of plausibility and verisimilitude, thereby attracting the user's sensory abilities and creating a convincing illusion of presence in the realm of the simulated reality.

High-quality graphics, precise motion tracking, spatial audio and visual cues, haptic feedback, and interactive input/output components must be integrated to make an immersive VR system. However, it's crucial to consider that levels of immersion can be subjective and differ from person to person because of differences in human perception and individual preferences. Factors such as motion sickness and prior experiences also affect the level of immersion. While immersion can be subjective and dependent on individual perception, here are some common levels of VR immersion:

2.2.3.1 Non-Immersive system

The lowest level of VR immersion, achieved without the need for powerful computing equipment, is the non-immersive VR system, commonly known as the desktop system. In this setup, the virtual environment is displayed on one or more screens of conventional computers. However, due to the absence of additional sensory input and limited interaction capabilities, the level of immersion is considerably low, mainly relying on basic visual cues. These desktop VR systems typically lack the sophisticated hardware and advanced technologies found in higher-end VR setups. As a result, they offer low-quality visual signals and may not provide the level of realism and interactivity associated with more immersive VR experiences.

Some desktop VR systems are integrated with haptic devices to address the limitations of visual-only interaction and increase the sense of immersion. Haptic feedback devices are peripherals that provide tactile sensations, allowing users to feel virtual objects and interactions. Incorporating haptic feedback makes the experience more interactive and realistic, enhancing immersion.

Desktop VR systems are often employed in various applications, including contemporary education. They serve as accessible and cost-effective solutions for introducing virtual learning experiences to students. These systems can offer simplified learning methods, allowing students to visualize concepts, explore virtual environments, and engage in interactive educational content. While desktop VR systems may not provide the highest level of immersion compared to more advanced setups, they still offer valuable opportunities for educational and training purposes, especially in settings where powerful computing equipment is not readily available or feasible. As technology advances, desktop VR systems may improve, offering increasingly immersive experiences even without the need for high-end hardware.

2.2.3.2 Semi-Immersive system

Semi-immersive VR systems, or fish tank or cave systems, represent an advancement over the basic desktop VR setup by incorporating additional features to enhance the perceived experience. These systems offer a more immersive environment by providing head tracking and navigation capabilities, allowing users to move and explore within a dedicated physical space. A typical CAVE system is shown in Figure 10. In semi-immersive VR systems, users are typically placed in a cube-shaped room or a similar setup, where the floors, walls, and ceilings serve as projection screens. This creates a surrounding visual environment that adds depth and realism to the virtual experience. As users move and interact with the surroundings, the optical flow of the projected visuals is dynamically updated based on their movement trajectory.

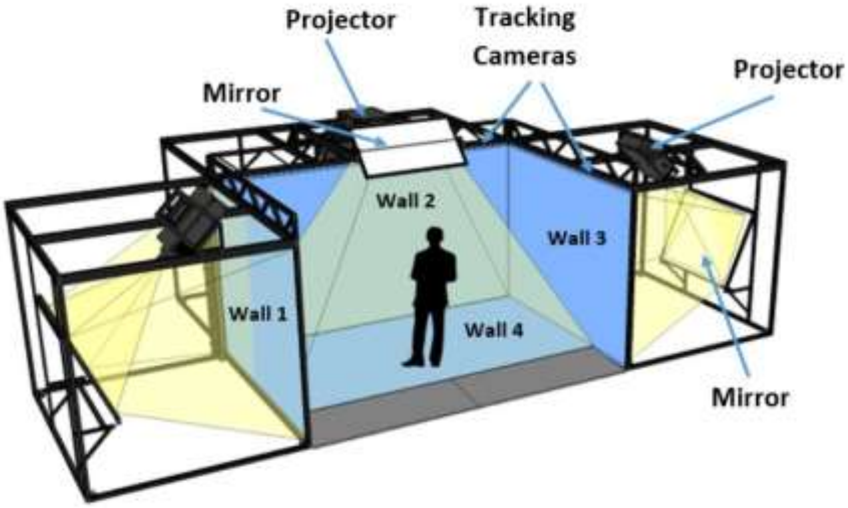

Figure 10: CAVE system

The introduction of head tracking is a crucial enhancement in semi-immersive systems. With head tracking, the system can detect the user's head movements and adjust the displayed visuals accordingly. As users turn their heads or change their viewpoint, the virtual environment responds accordingly, providing a sense of being present and immersed within the simulated world. Moreover, navigation is another key aspect of semi-immersive VR systems. The ability to physically move within the designated space allows users to explore the virtual environment more freely and naturally. The system fosters a greater sense of agency and interaction with the virtual world by enabling users to walk or move around.

Semi-immersive VR systems balance the simplicity and accessibility of desktop VR and the more sophisticated and costly fully immersive VR setups. They offer a level of immersion that surpasses basic desktop VR, making them suitable for various applications, such as architectural visualization, training simulations, and scientific exploration. While these systems do not provide complete sensory immersion in high-end VR environments, they offer an engaging and interactive experience that can be more conducive to certain types of applications, especially those that require some physical movement and interaction within the virtual space.

2.2.3.3 Immersive system

Immersive virtual reality (VR) systems represent an advanced technology that achieves heightened immersion, thereby providing users with an exceptionally realistic and engaging experience. These systems are characterized by incorporating a Head-Mounted Display (HMD) featuring an expansive field of view, which serves as the primary medium for delivering multisensory output. The amalgamation of haptic, auditory, and various other sensory interfaces within the immersive framework further contributes to the user's complete absorption within the virtual environment.

The Head-Mounted Display (HMD) employed in immersive VR systems enables users to perceive a three-dimensional perspective of the virtual world, continually adapting to users' head rotations and positional changes through precise monitoring mechanisms. As a result, users experience a seamless integration of their movements and actions with the virtual environment, fostering an intense sense of presence and engagement [10]. The versatility of immersive VR extends to a diverse spectrum of applications, encompassing domains such as gaming, flight simulation, scientific research, and a myriad of entertainment modalities. These immersive experiences have proven instrumental in enhancing user interactions, skill development, and situational learning, making them valuable assets in various professional, educational, and recreational contexts. Furthermore, the ever-evolving landscape of immersive VR technology promises continuous advancements, propelling the potential for even more realistic and impactful virtual experiences. As such, the proliferation and integration of immersive VR systems in multiple spheres will likely influence and redefine human experiences and interactions with digital environments.

2.2.4 Types of Immersion

Several types of immersion are commonly discussed concerning virtual reality (VR) experiences. These types of immersion can overlap and complement each other, contributing to a more engaging and immersive VR experience. There are four primary types of immersion; however, they are not mutually exclusive and often work together to create a more compelling and realistic VR experience, as explained below:

Tactile Immersion Tactile immersion, also known as haptic immersion, refers to the experience of virtual interaction with objects through the sense of touch. This immersion type is achieved by using haptic devices or data gloves that provide tactile feedback, allowing users to feel and manipulate virtual objects as if they were physically present. Haptic devices utilize force feedback or vibration to simulate the sensation of touching and interacting with objects in the virtual environment. When users interact with virtual elements, the haptic feedback provides a realistic sense of touch, creating a more immersive experience. The success of tactile immersion lies in the convincing and accurate replication of real-world tactile interactions. When users receive appropriate and responsive haptic feedback, they develop a heightened sense of presence and engagement within the virtual environment. This sense of presence is the feeling of being physically present in the virtual world, despite knowing it is a digital simulation.

Tactile immersion is particularly significant in applications where physical interaction is crucial, such as training simulations, virtual surgery, architectural design, and remote collaboration. In these scenarios, haptic feedback enables users to practice and learn in a safe and controlled environment while feeling a sense of realism and presence. As technology advances, haptic devices become more sophisticated, providing more nuanced and realistic tactile experiences. This advancement further contributes to the effectiveness of tactile immersion, enhancing the level of presence and immersion users feel during their interactions with the virtual environment.

Strategic Immersion The term "strategic immersion" aligns more closely with the description provided, emphasizing the cerebral nature of the immersion and the mental challenges associated with decision-making within the virtual environment. Strategic immersion involves engaging the user's cognitive faculties with complex and strategic choices. Like a chess player contemplating moves, users must analyze and assess various options available within the VR experience. Each decision has implications for their progress and success in the virtual world.

This immersion often revolves around scenarios that require tactical thinking, problem-solving, and long-term planning. Users are required to consider multiple factors, anticipate potential outcomes, and devise effective strategies to achieve their goals. Strategic immersion applies to VR experiences beyond chess, including real-time strategy games, management simulations, and decision-based narrative adventures. These applications provide users with intellectually stimulating and rewarding experiences, fostering a deeper level of engagement and a sense of agency within the virtual realm.

Narrative Immersion Narrative immersion refers to individuals' profound and captivating engagement within a story or narrative experience, where they become fully engrossed in the fictional world and the unfolding events. It is a state in which readers, viewers, or participants feel deeply connected to the characters, settings, and plotlines, often experiencing a sense of presence and emotional involvement. It is also classified into three categories: sensory immersion, cognitive immersion, and emotional immersion.

> **Sensory Immersion** Sensory immersion refers to engaging the user's senses to create a realistic and immersive experience. It requires high-quality visuals, spatial audio, and sometimes even haptic feedback to provide a sense of touch. The goal is to create an environment where users feel as if they are physically present in the virtual world through a multi-sensory experience.
>
> Sensory immersion is a multifaceted virtual reality (VR) concept that captivates the user's senses to generate a convincing and immersive experience. This approach entails integrating various sensory elements, including high-fidelity visuals, spatial audio, and, in some instances, haptic feedback, to stimulate the user's sight, hearing, and touch. The primary objective is to engender an environment where users perceive themselves as physically present within the virtual world, achieved through the seamless integration of a multi-sensory encounter.
>
> Central to sensory immersion is the utilization of cutting-edge visual rendering techniques to create lifelike and highly detailed virtual environments. These high-quality visuals, in combination with spatial audio technologies, foster a sense of spatial presence, enabling users to locate virtual sounds in three-dimensional space acoustically. By extending the sensory engagement to touch, haptic feedback mechanisms are employed, allowing users to experience tactile sensations and interactions with virtual objects.

Cognitive Immersion The term "cognitive immersion" describes the level to which a person is mentally involved in a VR experience. The factors contributing to this include the richness of the narrative, tough riddles, and intricate gameplay mechanics that contribute to this level of immersion. Users experience cognitive immersion when fully immersed in the virtual environment and its story. Cognitive immersion is essential for creating meaningful and impactful VR experiences, especially in educational, training, and severe gaming applications. When users are mentally absorbed and invested in the virtual environment and its narrative, they are more likely to retain information, learn new skills, and experience a deeper level of engagement. Developers and content creators strive to design VR experiences that trigger cognitive immersion through thoughtful storytelling, challenging gameplay, and meaningful interactions, ultimately providing users with a more enriching and transformative virtual reality encounter.

Social Immersion Social immersion refers to creating means of presence and interaction with other users present within the VR environment. This type of immersion can be achieved by developing multiplayer experiences, where users can communicate, collaborate, or compete with others in real time. Social immersion holds excellent potential for various applications in VR, including virtual meetings, virtual events, online social gatherings, and collaborative training scenarios. Users can experience a sense of community and companionship by enabling social interactions in virtual spaces, transcending geographical boundaries and physical limitations. Using avatars, audio chat, and shared activities enhances social immersion, connecting users to a virtual community.

Developers and designers continually explore ways to enhance social immersion in VR, as it significantly impacts user engagement, satisfaction, and overall enjoyment of the virtual experience. As VR technology continues to evolve, the potential for social immersion to transform how people connect and interact in the digital realm is vast, opening new avenues for social experiences and fostering a more connected virtual world.

2.2.5 Characteristics of Immersive VR system

An immersive VR system is designed to provide a highly engaging and realistic virtual experience. Here are some key characteristics of immersive VR systems [9]:

1. Immersive VR system aims to achieve a sense of "presence and depth" where the user feels fully immersed and believes they are physically in the virtual environment. This can be achieved through high-quality stereoscopic image visuals, 3D audio, and other interactive elements.
2. It requires high-quality visual displays to present stereo images to the user using head-mounted displays (HMDs). Stereo images generated by these HMDs and a wide field of view and high-resolution screens provide a detailed and expansive visual experience.
3. Immersive VR systems incorporate tracking mechanisms to monitor the user's head and body movements. The user's perspective is adjusted as he moves his head or body, giving him a more immersive feeling.
4. 3D Spatial audio technology is used in immersive VR systems to produce realistic soundscapes. Combined with visual display, these audio cues generated from different angles and distances increase the sense of presence and immersion.

5. Engagement and level of interactivity are the key elements for creating an immersive VR environment. It allows users to engage with and manipulate virtual objects like in the real world. This can be achieved using motion controllers, haptic feedback devices, or gesture recognition systems.
6. Immersive VR systems strive for high-quality graphics and realistic visual rendering. Advanced rendering techniques such as real-time shading, global illumination, and texture mapping create detailed and visually appealing virtual environments.
7. Some immersive VR systems also incorporate haptic feedback devices to provide tactile sensations to the user. These devices can simulate touch, vibrations, and force feedback, enhancing the sense of realism and immersion by allowing users to feel virtual objects or interactions.
8. Multiuser experience is an added feature of some VR systems that enhance social immersion, allowing multiple users to interact and collaborate within the same virtual environment.

2.2.6 Equipment for a VR System

VR systems typically consist of several key components and equipment used as a source of interaction between the real world and the virtual world [11]. Here are the primary elements commonly used in VR systems:

Head-Mounted Display (HMD): The HMD is a wearable device worn on the head and covers the user's eyes, providing a virtual visual experience as shown in Figure 11. It typically consists of two high-resolution displays, one for each eye, and lenses that help create a stereoscopic 3D effect and an immersive 3D perspective of visual stimulation. HMDs may also include built-in sensors for tracking head movements.

Figure 11: Head-Mounted Display

Motion Tracking System: For tracking the user's head and body movements, VR systems incorporate motion tracking technology. This can involve various methods such as inside-out tracking (using built-in cameras on the HMD to track the environment), outside-in tracking (using external cameras or sensors to track markers or devices on the user), or sensor-based tracking (using inertial sensors or external trackers) as shown in Figure 12.

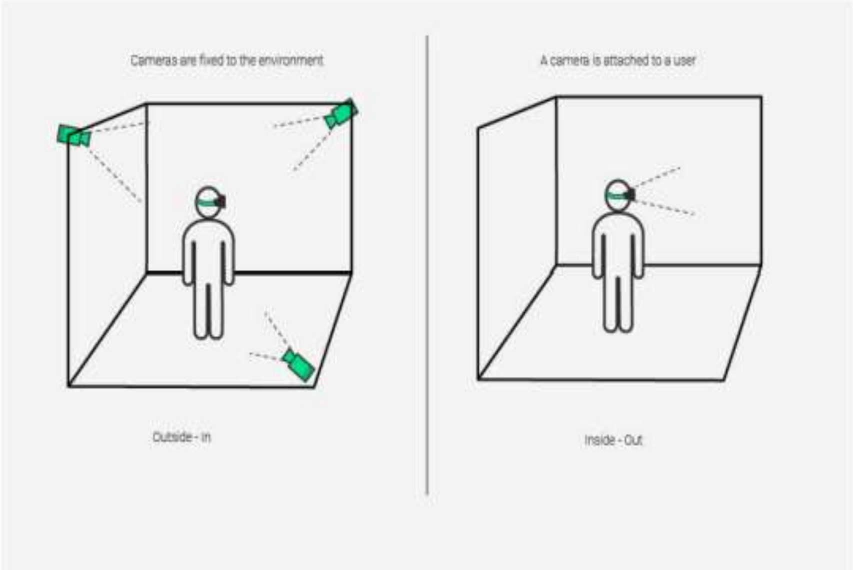

Figure 12: Outside In vs. Inside Out tracking

Input Devices: The users interact with the developed VR environment using various input devices. This can include multiple devices such as handheld motion controllers that track the user's hand movements, buttons, or touchpads on the controllers for input commands. Some specialized devices are also being used, such as data gloves for more precise hand and finger tracking (Figure 13), voice identification, and retina or eyeball tracking technology.

Figure 13: HMD with tracking gloves

Audio Devices: For an immersive VR experience, high-quality audio is essential. Generally, HMD has built-in headphones that provide spatial audio by simulating sound from different directions. Alternatively, external headphones or speakers can be used for audio output.

Computing Hardware: Powerful computing hardware is crucial for rendering a virtual environment with high resolution and spatial cues. This includes a robust CPU (Central Processing Unit), a powerful GPU

(Graphics Processing Unit) to handle the graphics processing, sufficient RAM (Random Access Memory), and storage space to store and update VR content in real-time.

Tracking Area or Sensors: Some VR systems require a designated tracking area or sensors placed in the room to enable room-scale VR experiences. These sensors, such as infrared or laser-based tracking systems, track the position and movement of the user within the physical space, allowing them to move freely and interact in the virtual environment as shown in Figure 14.

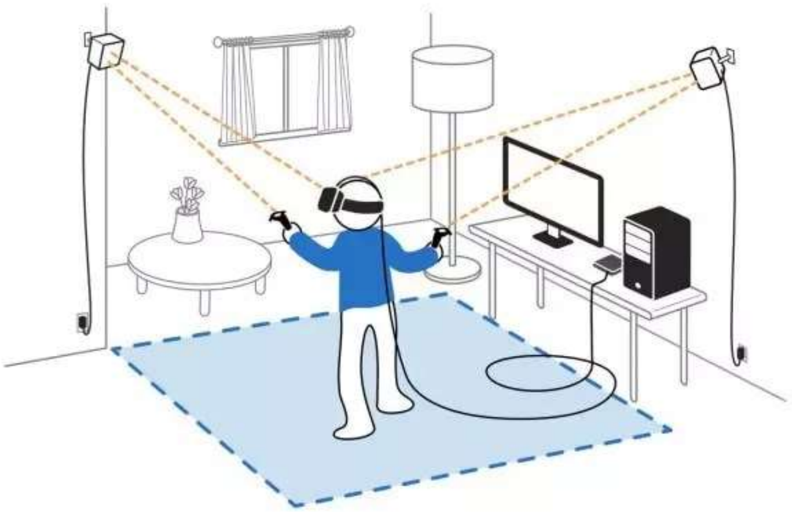

Figure 14: VR tracking

2.2.7 Applications of Virtual Reality

Virtual reality (VR) has a wide range of applications across various domains of life. Here are some typical applications of VR [12]:

Education and Learning: VR is used in the educational field to create engaging and interactive learning experiences. It allows students to explore historical sites, travel to different countries, or visualize complex concepts of science in a more immersive manner. VR can provide a hands-on approach to learning, enhancing retention and understanding.

Healthcare and Therapy: VR is used in healthcare for various objectives, such as pain relief, surgical training, and mental health therapy. It may be used to provide exposure therapy for phobias and anxiety disorders, imitate medical procedures, build immersive worlds for diversion during uncomfortable treatments, and more. The technology is also used in cognitive behavior therapy, providing phobia and anxiety sufferers with a secure environment to solve their problems.

Training and Simulation: VR provides a safe and cost-effective way to train individuals in various fields. It simulates real-world scenarios in the aviation, military, healthcare, and emergency services industries. VR training allows users to practice skills, decision-making, and critical thinking in a realistic and controlled environment.

Architecture and Design: VR is utilized in architecture and design to create virtual walkthroughs of buildings and environments before construction. It allows architects, designers, and clients to visualize and experience the space, make design decisions, and identify potential issues.

Automotive industry: Virtual reality has saved enormous costs for the automotive industry. Before going towards prototype development, automotive engineers can review the object obscuration and visual design of the vehicle. The virtually developed prototype enables them to validate the system specifications against the desired requirements before going toward the development phase.

Gaming and Entertainment: VR is extensively used in the gaming industry to create immersive and realistic gaming experiences. Users can interact with virtual worlds, characters, and objects, enhancing their gaming experience.

Tourism and Exploration: VR offers virtual travel experiences, enabling users to visit destinations they may not be able to access physically. It allows people to explore landmarks, natural wonders, and cultural sites from their homes.

Collaboration and Communication: VR enables remote collaboration and communication in virtual environments. Multiple users can interact, share information, and work together in real-time, even if they are physically located in different places.

2.3 Flight Safety

Safety is paramount in any system involving human participation, and in aviation, flight safety is the most essential and highly prioritized element. Flight safety encompasses a comprehensive set of measures, protocols, and practices to ensure the secure operation of aircraft and safeguard the lives of passengers, flight crew, and the general public. The ultimate goal of every flight is to take off and land safely, a routine occurrence that happens over 100,000 times (approximately) every day worldwide [13]. To achieve this, the aviation industry implements a broad range of practices, regulations, and systems designed to minimize the risk of accidents and incidents in aviation. Given the inherent risks of air travel, the aviation industry significantly emphasizes flight safety. The operation of aircraft involves numerous complex systems, and any malfunction or pilot error may lead to severe consequences. As a result, the discussion of flight accidents and safety procedures remains a continuous and critical topic at all aviation forums.

Many strategies and procedures are continually updated and implemented to mitigate risks and ensure a safe aviation environment. These include rigorous training programs for flight crew, regular aircraft maintenance and inspections, air traffic control systems to manage airspace, stringent safety regulations, and ongoing monitoring and analysis of flight data to identify potential areas of improvement. Through a collective commitment to flight safety, the aviation industry continuously strives to enhance safety standards and maintain high safety performance. The collaboration of regulatory authorities, airlines, manufacturers, pilots, air traffic controllers, and other stakeholders is crucial in upholding the highest safety standards in aviation.

By prioritizing and investing in flight safety, the aviation industry ensures that air travel remains one of the safest modes of transportation available. The unwavering focus on safety contributes to the confidence and trust passengers place in the aviation system, making air travel an indispensable and reliable means of global connectivity.

2.3.1 Factors contributing to flight safety

Flight safety is a multidimensional endeavor encompassing numerous factors, including aircraft maintenance, pilot training, air traffic control, safety management systems, regulatory compliance, technological advancements, and data analysis. The continuous efforts of aviation stakeholders, including airlines, pilots, regulators, and manufacturers, are crucial in maintaining and improving flight safety standards. By prioritizing safety, the aviation industry strives to provide passengers with a secure and reliable mode of transportation.

2.3.1.1 Aircraft maintenance

One of the fundamental aspects of flight safety is aircraft maintenance. Regular inspections, repairs, and scheduled maintenance checks are conducted to ensure that the aircraft is in optimal condition for flight. Highly skilled technicians and engineers meticulously examine the aircraft's systems, structure, and components to identify any potential issues and address them promptly. This proactive approach helps prevent mechanical failures and malfunctions during flight.

2.3.1.2 Expertise of Pilots

Furthermore, flight safety heavily relies on the expertise and competence of pilots. Pilots undergo extensive and recurrent training programs that cover theoretical knowledge, practical skills, and simulated flight scenarios [14]. This training covers routine scenarios and handles various situations, including emergencies, adverse weather conditions, and technical malfunctions. Additionally, pilots undergo refresher training programs and proficiency checks to polish their skills and stay updated with the latest procedures and technologies.

2.3.1.3 Air Traffic Control

Another critical component of flight safety is air traffic control (ATC). ATC consists of skilled personnel who monitor aircraft paths, guide movements to ensure proper separation between airplanes and provide guidance during takeoff, landing, and en-route phases. Highly sophisticated radar systems and communication equipment is used by controllers to track and monitor flight path and to coordinate with the pilots. The undisrupted collaboration between pilots and air traffic controllers is essential in preventing mid-air collisions and ensuring smooth operations.

2.3.1.4 Safety Management system

Safety Management System (SMS) is a proactive and systematic approach to managing organizational safety risks. It involves different processes such as risk assessment, incident reporting and investigation, safety training, and continuous improvement processes [15]. By fostering a culture of safety and accountability, SMS aims to identify and address potential hazards before they lead to accidents.

2.3.1.5 Following Intl Standards

The implementation of international standards and regulations also contributes to flight safety. Global organizations such as the International Civil Aviation Organization (ICAO) establish global guidelines and requirements for aviation safety. These standards include aircraft design and manufacturing, pilot training and qualification standards, airport operations, and air traffic control procedures. Adherence to these standards ensures a constant and high level of safety throughout the aviation industry.

2.3.1.6 Technology

Technological advancements have significantly enhanced flight safety as well. Modern aircraft have advanced avionics, navigation systems, and onboard computers that provide fast real-time data, improve situational awareness, and automate specific tasks. These technologies assist pilots in monitoring flight parameters, avoiding hazardous weather conditions, and optimizing fuel efficiency. Furthermore, advancements in aircraft design, components and materials, and engineering techniques contribute to improved safety and reliability.

2.3.1.7 Flight Data Analysis

Collecting and analyzing flight data are indispensable aspects of flight safety, providing invaluable insights into aviation operations and contributing to continuous safety improvements. Flight data recorders, often referred to as "black boxes," are critical devices that record a comprehensive range of flight parameters and cockpit communications throughout a flight. The wealth of data captured by these flight data recorders includes crucial information such as altitude, airspeed, heading, vertical acceleration, control inputs, engine performance, and various system statuses. Additionally, cockpit voice recorders (CVRs) capture the audio communications between the flight crew, enabling investigators to reconstruct the interactions and decision-making processes in the cockpit. In the unfortunate event of an accident or incident, the data stored in the flight data recorders becomes an essential resource for aviation authorities and accident investigators. By meticulously analyzing the recorded data, they can accurately reconstruct the events leading up to the incident and determine the factors contributing to the outcome. This process is critical in identifying the root causes of accidents and developing practical safety recommendations to prevent similar incidents from occurring. Flight data analysis is also valuable for identifying potential safety risks and performance trends. By continuously monitoring and analyzing flight data, aviation experts can identify anomalies, trends, and patterns that may indicate the need for corrective action or improved safety procedures. This proactive approach enables the aviation industry to address safety concerns before they escalate into serious incidents.

2.3.2 Human factor and flight safety

The human factor plays a prominent role in aviation safety and has been identified as a crucial contributor to aviation accidents and incidents. It includes all aspects related to human performance, skills and limitations, and attitudes toward the safety and operation of flights [16,17]. To mitigate risks, enhance safety procedures, and improve the industry's overall safety culture, it is crucial to comprehend the human aspect. Several aspects fall into the category of human factors, such as human error, crew resource management, fatigue, stress and workload, organizational culture, and leadership.

2.3.2.1 Human error

Humans are imperfect, and errors may occur at any stage of flight operations, from pre-flight planning to post-flight procedures. Human errors can be categorized into two main types: skill-based errors and decision-based errors. Skill-based errors occur due to lapses in manual skills, such as improper handling of controls or inadequate monitoring of systems. Decision-based errors, on the other hand, result from flawed judgment, poor situational awareness, or failure to consider all available information.

To minimize the impact of human errors, error prevention, and management is mandatory. Error prevention strategies include comprehensive pilot training, implementation of standard operating procedures (SOPs), teamwork, and effective communication. Error management includes implementing safety nets and redundant systems, such as automation and checklists, to detect and mitigate errors before they cause havoc timely.

2.3.2.2 Crew Resource Management

Another important human factor aspect is crew resource management (CRM). CRM refers to the effective and balanced use of all available resources of the organization, including human, technical, and informational, to ensure safe and efficient flight operations. It emphasizes communication, teamwork, leadership, and situational awareness among the flight crew. By undergoing CRM training at an organizational level, supervisors can distribute workload among crew members, effectively make decisions, and proactively address potential risks or errors.

2.3.2.3 Fatigue

Fatigue is another significant human factor that can compromise flight safety. Pilots and crew members often work irregular schedules, operate on long-haul flights, and cross multiple time zones, leading to sleep deprivation and circadian rhythm disruptions. Fatigue can impair cognitive abilities, reaction times, decision-making, and situational awareness. To address this issue, aviation authorities and airlines have implemented regulations and guidelines governing flight and duty time limitations to prevent pilots from flying when excessively fatigued.

2.3.2.4 Stress and workload

Stress and workload also impact the human factor and flight safety. High-stress situations, such as emergencies or adverse weather conditions, can affect a pilot's cognitive functioning and decision-making abilities. Similarly, excessive workload can lead to information overload, distraction, and reduced situational awareness. Pilots and crew members must manage stress effectively, prioritize tasks, and delegate responsibilities to maintain optimal performance and safety.

2.3.2.5 Communication

Effective communication is a key component of human factors in flight safety. Clear and concise communication is the key to maintaining situational awareness, exchanging crucial information, and coordinating actions pertaining to flight operations. Any miscommunication may lead to a compromise on the safety of all concerned. Therefore, aviation personnel are imparted with continuous training to enhance their communication and practical skills.

2.3.2.6 Organizational culture

Lastly, organizational culture and leadership significantly impact the human factor and flight safety. Airlines and aviation authorities are vital in fostering a safety culture, emphasizing open communication, reporting safety concerns, and continuous learning and improvement. Strong leadership encourages all the crew members to follow safety guidelines and procedures, maintain effective communication to bridge the gaps among team members, and address potential risks or hazards.

2.3.2.7 Pilot training and expertise

Pilot expertise encompasses a comprehensive understanding of aviation principles honed through extensive knowledge, experience, and skill. This expertise blends technical prowess with adept decision-making, enabling pilots to operate aircraft safely. Proficiency in aircraft systems, navigation, weather analysis, and flight maneuvers underscores their ability to ensure secure journeys. Ultimately, pilot expertise embodies the fusion of specialized know-how, quick judgment, and an unwavering commitment to aviation's fundamental principles.

2.3.2.7.1 Aircraft handling and flight operations

Pilots are well-versed in various segments of flight operations, including pre-flight checks, knowledge of aircraft systems, navigation, flight planning and scheduling, fuel management, and communications with ground staff. A pilot must know the procedures and protocols to ensure safe and efficient flight operation. He has the skills to operate and control an aircraft, including takeoffs, landings, climbs, descents, and maneuvers. For a safe flight, he must possess a high level of manual dexterity, hand-eye coordination, and motor skills to manipulate the controls precisely. This, the most critical factor, is important in any aviation setup. A well-trained and skilled pilot is the key to ensuring safe and smooth flight operations.

2.3.2.7.2 Navigation and Instrumentation

Besides basic aircraft handling, pilots must thoroughly understand navigation techniques, such as charts, GPS, and navigational aids. They have to be proficient in interpreting the instruments and avionics of the aircraft, allowing them to navigate accurately under various conditions, including low visibility or instrument flight.

2.3.2.7.3 Risk Assessment and Emergency Procedures

Besides regular/routine flying, pilots are trained to handle emergencies, such as engine failures, system malfunctions, or adverse weather conditions. They should have the expertise to assess different risks, make prompt decisions, and execute appropriate procedures to handle the emergency and ensure the aircraft's and its occupants' safety. For this, they are trained to have effective and timely decision-making skills and the ability to assess risks effectively. Considering factors such as the performance of various aircraft systems, weather conditions, fuel reserves, air traffic, and passenger safety are equally important to make informed judgments and take the best course of action [18].

2.3.2.7.4 Situational Awareness

Situation awareness, from the eyes of Endsley, is a term designating a person's internalized mental model of the current state of the environment. It includes the perception of the environment, cognition of the system's current state, and projection of the plausible outcomes in the near future. The setting may vary based on the nature of the task and participants, including objects, people, mechanical systems, or other less tangible features. This mental model, developed by the critical actor of the play, is the basis for further decision-making and definition of their actions in a dynamic world. Considering the scenario of a tactical military pilot flying in an operational mission, the level of difficulty and complexity of the situation is heightened due to time constraints [19]. Their prompt decision-making during combat missions (in seconds) may end up in extremes, i.e., a war-winning scenario complementing operational readiness or a defeat in a fatal incident. Thus, situation awareness becomes similar scenarios' most critical yet significant element.

2.3.2.7.5 Continuous Learning and Adaptability

Pilots embrace a mindset of continuous learning and adaptability. They undergo training to stay updated with new technologies, industry best practices, and regulatory changes, actively seeking opportunities to enhance their skills and knowledge. There are recurrent training programs to ensure they stay abreast of the newest technology, system upgrades, emergency handling, and accident prevention plans. These training programs include daily post-flying briefs, refresher training, and simulator training. It's important to note that pilot expertise and skills develop over time through experience, training, and ongoing learning. The level of knowledge may vary among pilots based on their experience, specialization, and dedication to polishing their skills.

2.4 Flight simulators and pilot performance evaluation

Simulators are widely used for various training tasks, especially in areas requiring unique skills that can only be obtained through practice or hours of flying time. A novice can learn the functioning of a complex tool or a system through the simulator. In aviation, especially in pilot training, a pilot must carefully know the correct aircraft procedures and the uses of each panel or tool. Using a flight simulator compared to actual flight provides benefits in terms of flight safety, the most significant factor, be it military or civil aviation, and expertise, i.e., pilots can fly variable scenarios of routine nature, unusual or even life-threatening events. Advances in present-day technologies have rendered several possibilities for simulator-based flight training. Any new aircraft technology, be it fly by wire control system design, advanced glass cockpit design, or finalizing head up/down display symbology, is developed to increase aircraft/pilot usability and ease the pilot's role and task.

Virtual reality (VR) is a new and promising technology that enriches the user with an immersive experience and human perception of being in the real world by stimulating sensory cues [20]. These features make it an ideal choice for flight training in which the user/pilot needs to be fully immersed during flying experiences. Emerging technologies in flight simulation help evaluate the usability of the technology used through pilot opinion. For these evaluation objectives, commonly used methods include subjective measurements, which are quick and non-intrusive, but the judgments rely highly on personal views and situational aspects at that instant. Hence, these methods alone may not always be sufficient. Therefore, using quantitative tools and techniques along with the pilot ratings can give more meaningful judgments. These measurements can approximate the pilot's cognitive workload and aircraft's system-level errors along with the inefficiencies of their flight performance during that dedicated flight.

There are two broad categories of means of pilot performance assessment, i.e., subjective and objective [21,22]. Subjective or qualitative evaluation is based upon feedback methods, which can be in the form of personal observations or feedback from an expert such as a well-trained instructor pilot. These evaluations incorporate factors that may not be easily quantifiable but are still considered equally important for assessing pilot performance. Objective evaluation methods are the direct means to determine the performance of pilots based on a predetermined objective scale. It uses a quantifiable and measurable criterion to assess pilot performance. This criterion relies on specific metrics pertaining to flight data and globally accepted civil aviation standards, leaving little room for personal interpretation and error in evaluation.

Some examples of subjective evaluation methods include observational Assessments, i.e., flight instructors observe and assess a pilot's decision-making, communication, situational awareness, crew coordination, and adherence to procedures. These assessments include subjective judgments based on their personal observations and expertise. Another method of subjective assessment is CRM evaluation. This focuses on evaluating teamwork and communication skills, leadership qualities, and decision-making within a flight crew. Subjective judgments of the pilot's interaction with other crew members are based on a pre-built scale. Direct interviews from the pilots can also help to establish an insight into the pilot's skills, performance, and workload level he is facing during the flight. Feedback Proforma and personal interviews are used for this purpose. Subjective evaluation techniques allow for a more holistic evaluation of a pilot's performance, including elements that quantitative/objective measurements would find challenging to include. They offer a more in-depth comprehension of a pilot's skills, human elements, and general efficacy in real-world situations. A major drawback of subjective measures is a lack of correlation between raters on specific criteria that constitutes successful performance. Contrarily, rater variability does not affect objective procedures if reasonable tolerance levels are implemented to consider pilot variability.

Automated performance assessment, component/total task performance, residual attention, tracking tasks, dual-task performance, task taxonomy creation, and modeling methodologies are examples of measures in the objective category. Due to the data-collecting possibilities simulators offer, automated performance measurement constitutes a relatively recent performance measurement advancement. The fact that aircrew performance necessitates automated data collecting methods due to its constantly changing nature is its main benefit. Most of the research work in this domain is based on the assumption that pilot performance is directly reflected in specific flight parameters (for example, airspeed and altitude), which must be maintained to the predefined tolerance limits [22]. This method, also known as flight data monitoring, captures flight parameters such as altitude, airspeed, heading, aircraft control inputs, navigation, radio procedures, etc. Analysis of this data and comparison with the predefined tolerance limits can provide insights into adherence to standard operating procedures, measure flight deviations, and assess overall flight performance. It has been shown that the "diagnostics" may not directly relate to pilot performance but help interpret the error; further study of the pattern of errors can help build trend analysis, and more meaningful data is collected. As indicated by the literature, the main emphasis is that automated performance measuring systems should be put through empirical utility testing, paying close regard to the designated tolerance thresholds for each metric [23]. Standardized written tests or practical assessments also measure a pilot's knowledge and proficiency in specific areas. These tests typically have precise and true-false answers and scoring criteria, enabling objective assessment of the pilot's understanding and competency. Some other performance metrics, such as fuel consumption, on-time departures, or compliance with standards and regulatory requirements, can be objectively measured and evaluated to assess a pilot's performance.

It is well-known that a pilot’s cognitive workload highly impacts their performance and, in turn, affects smooth flight operations and the safety of the flight. A higher workload results in less attention and focus of pilots on the task, which deteriorates their performance [24]. Contrarily, an extremely low workload may cause boredom, resulting in poor performance. These constraints need to be considered well before the design optimization of pilot interface panels. This is only possible if a pilot’s cognitive workload is accurately estimated. However, as flying an aircraft is a tedious task, a large number of physiological and psychological factors are to be taken into consideration. This is also categorized as one of the pilot’s performance evaluation methods and subjective and objective assessments. Even though subjective evaluation techniques such as the NASA TLX index calculator or Cooper Harper ratings are more customarily used, research in this domain proves that physiological variables are more sensitive for estimating pilots' cognitive workload [25]. Different techniques incorporating a wide range of parameters are being explored in available research, such as heart rate variability (HRV), galvanic skin response (GSR), eye tracking, and spatial disorientation [26]. The study reveals that physiological measures provide more insight into pilots' performance evaluation than subjective measures. Another study finding is that an individual’s cardiac activity is a valuable measure of cognitive processes. In one more study, the percentage of mean pupil dilation was analyzed with subjective techniques by Othman and Romli (2015) [27] as part of their multi-index evaluation for estimating cognitive effort.

According to recent research by Mohanavelu et al. [28], HRV characteristics, pilot performance measurements, and subjective evaluation methods might all be used to gauge how different visibility circumstances affect pilots' mental workloads. Despite identical performance scores across pilots, it was discovered that the physiological measurements were statistically significant. According to a comparison research by Gentili et al. [29], HRV was less responsive to changes in cognitive effort [30] characteristics than EEG. Based on this research, it is evident that sufficient work has been done to explore the effect of psychophysiological measures [31] such as brain-related studies (ERP, EEG, MEG, and brain metabolism), ocular measures (fixations, scan path, blinks, and pupil diameter), cardiac measures (HRV), and facial expression measures [32]. However, there is little research where multiple methods are studied simultaneously in a controlled environmental setup. Furthermore, studies are scarce to compare and establish correlations among distinct autonomous physiological and pilot performance metrics.

2.5 Virtual Reality Flight Simulator related research

A virtual reality flight simulator (VRFS) is a technology that combines virtual reality (VR) and flight simulation to create a realistic flying experience. It allows users to immerse themselves in a virtual environment and experience flying an aircraft. A typical VRFS uses a head-mounted display (headset) to create a 3D view. The headset tracks the user's head and eye movements, allowing them to look around and interact with the virtual environment [33]. Additionally, the simulator may include other hardware components such as a joystick, throttle, and pedals to provide a more realistic control interface. The VRFS software generates a virtual world replicating real-world landscapes, airports, and aircraft. Users can select among different aircraft types, sceneries/areas, and flight configurations and plans using the software interface. More sophisticated software simulates flight physics and provides options to select weather conditions, different emergencies, and other factors to create a realistic flying experience [34,35].

Virtual reality flight simulators are used for various purposes, including pilot training, entertainment, and aviation enthusiasts. They provide the added advantage of being a safe, accessible, and cost-effective way to practice flight maneuvers, learn instrument procedures, and improve flying skills. Virtual reality enhances the immersion and realism of the experience, making it feel like you are flying an aircraft. Besides training [36], VRFS can also be used for entertainment, allowing users to experience the delight of flying without needing an actual aircraft. Some virtual reality flight simulators even support multiplayer functionality, allowing users to fly together in the same virtual airspace or participate in air races and combat scenarios.

It's fascinating to see how VR technology has been utilized to develop various flight simulators, enabling a more realistic and cost-effective flight environment. Air Force Institute of Technology's Distributed Interactive Simulation [37] was an early demonstration of a virtual cockpit for flight simulation. It proved a significant step in utilizing VR technology for aviation purposes. The concept of distributed interactive simulation allowed multiple users to participate in the virtual environment simultaneously, fostering collaboration and training opportunities. The University of California achieved the development of a reconfigurable virtual cockpit using head-mounted displays (HMDs), which showcased the potential of VR in creating adaptable and immersive flight environments [38]. This innovation likely provided a more flexible and personalized training experience for pilots. Figure 15 shows the reconfigurable virtual research cockpit.

Later on, Middle East Technical University developed a VR-based Helicopter Simulation [39], as shown in Figure 16. Creating a VR-based helicopter simulation addressed the specific needs of helicopter pilots. Such simulations offer a tailored experience that focuses on the unique challenges of helicopter flight, allowing pilots to practice maneuvers and procedures in a safe and controlled environment.

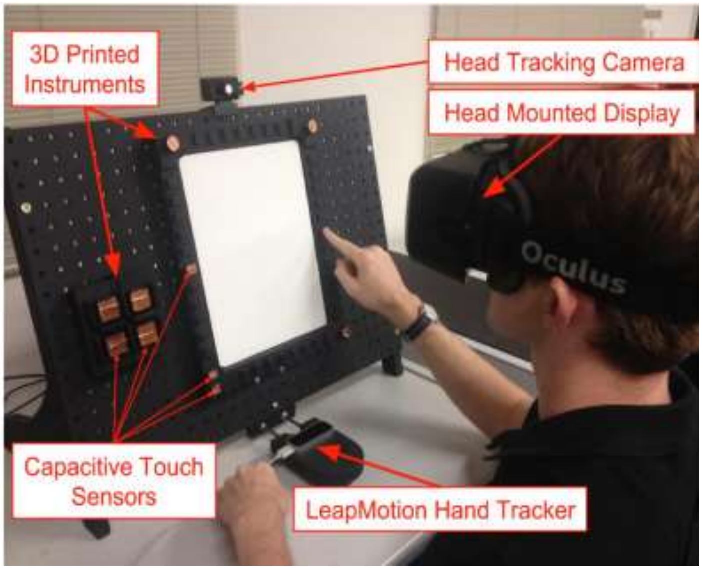

Figure 15: The rapidly configurable research cockpit

The Virtual Reality Flight Simulator (VRFS) developed by Oberhauser and Dreyer [40] likely represents a culmination of advancements in VR technology for flight simulation. This simulator could have incorporated various features from previous works to create a comprehensive and highly realistic flight training platform. Overall, the main objectives behind developing these VR flight simulators were to offer a cost-effective means of training pilots and simulating the flight environment that closely mimics real-world scenarios. VR technology's immersive nature allows for a more engaging and practical learning experience, promoting skill development and enhancing safety in aviation training. As VR technology continues to advance, we can expect even more sophisticated and realistic flight simulation systems in the future.

Figure 16: A virtual reality flight simulator

Widely published research studies VR flight simulation in the context of psychological disorder therapy. A study was conducted by Mu¨hlberger [41] to examine the effects of repeated exposure to VR flight simulation on individuals with flight phobia. The results indicated that exposure to VR flight simulation positively reduced fear and was particularly effective when combined with relaxation training. This suggests that VR-based exposure therapy can be a valuable tool in helping individuals overcome their fear of flying. Rothbaum [42], in his study, compared the effectiveness of exposure therapy for fear of flying in two contexts: actual aircraft and VR flight simulation. The findings showed that VR-based exposure therapy was as effective as exposure to the actual aircraft.

Additionally, participants who underwent VR-based exposure therapy experienced a significant reduction in fear compared to a control group that received no treatment. This suggests that VR flight simulation can provide a realistic and impactful exposure experience for individuals who fear flying. Overall, the research demonstrates the potential of VR flight simulation as a valuable tool in treating psychological disorders, such as flight phobia. By providing a safe and controlled virtual environment, VR allows individuals to confront their fears gradually and repeatedly, reducing fear and improving psychological well-being. Additionally, VR flight simulation shows promise in other aviation-related applications, such as human factors engineering and pilot training, as it provides a cost-effective and immersive training environment.

In a study by Oberhauser and Dreyer [40], researchers developed a VR flight simulator with a mixed-reality mock-up that combined VR headsets and hardware in the cockpit. Experienced commercial airline pilots and non-pilots participated in a series of experiments to evaluate the fidelity and usability of the VR simulation compared to a full-flight simulator. The mockup setup is shown in Figure 17.

In the experiment, the pilots had to complete flying tasks, operate different buttons and switches (both virtual and non-virtual) in the cockpit, and interact with the touch-based console. During the experiment, the supervisor played the co-pilot role to ensure compliance with the nature and sequence of flight tasks. The collected data included the Pilot’s heart rate and heat maps of eye tracking as well. As depicted by the results, the overall operational behavior of pilots in VR is comparable to the full flight simulator environment, as the VR flight model had a sufficient simulation fidelity and usability level to fulfill the stated tasks in a time-confined scenario [40]. The VR flight simulation might be an effective method for gathering credible information on human factors interactions during flights. Some of the limitations of using VR flight simulation were also highlighted. This includes slower users' movements and more time required to finish the tasks, such as pressing virtual buttons (non-haptic), as reported by the pilots. A few participants also complained that the VR equipment wasn't very comfortable to wear, and users might get simulation sickness when flying in VR [43].

Figure 17: Mixed Mock-up and full virtual interaction by Oberhauser (2017)

In a separate study, Oberhauser [44] compared the efficacy of pilots in a virtual reality (VR) flight simulation environment and a traditional flight simulation environment. Figure 18 illustrates how the cockpit of the hardware simulator was modified and integrated into the VR experience. The VR simulation required the user to wear an HMD and have tracking targets affixed to their hands. In this configuration, the user can interact with the control element in the virtual reality environment while also contacting the control element on the actual hardware, resulting in the corresponding haptic sensation.

The study employed a within-subject design model; 28 pilots with a mean age of 42.5 years and average total flight time of 2,485 hours were asked to perform a left-hand traffic pattern once in the VR simulation and once in a conventional FTD. Outside visuals were projected in the case of the conventional simulator. Before experimenting, all participants flew a left-hand traffic pattern for familiarization with each simulation environment. The flight starts with a short taxiing phase from the parking position, takes off, and flies a left-hand traffic pattern at 2,000 ft. The participants receive pre-recorded audio commands to interact with different cockpit components during the scenario. After a touch-and-go and a repeated left-hand pattern, the participants performed a full-stop landing. Dependent measures studied in this experiment include the Movement Time (the time taken by the pilot to reach the cockpit control element after receiving the audio command) and deviation of flight parameters, i.e., Heading, Altitude and Lateral touchdown deviation, Runway heading alignment error, and Final approach cross-track error in comparison to the set flight path. Pilots' workload was also calculated using the NASA-Task Load Index (TLX) and the Simulator Sickness Questionnaire (SSQ). It was found that movement time in the VR flight simulation was comparatively longer than in the conventional flight simulation.

Figure 18: VR flight simulator by Oberhauser (2018)

Similarly, the deviations calculated for flight data were significantly more in VR than in the conventional flight simulation. The pilots' workload (mental, physical, temporal demand, effort, and frustration), as calculated by the NASA-TLX, was significantly higher in the VR than in the conventional flight simulation, which was in relation to the self-rating of pilots. Participants reported higher symptoms of simulator sickness in VR flight simulation. The study discussed that the degraded performance in VR might be influenced by several factors, such as the non-familiarity of the participants with the VR equipment, the inaccuracies in the virtual hand model and latency of VR input to display path (50 ms), and limited field of view of the VR headset. All the participants could safely land the aircraft in both environments, implying that the degraded performance does not affect safety. Notwithstanding the drawbacks observed in the existing VR flight simulation compared to conventional flight simulation, the advancement of VR technology is promising to serve as a valuable resource for training and research purposes—the endorsement and accreditation of VR-based flight training hinge upon this realm's prospective advancements and endeavors.

McGowin did a research study in 2020 showing that VR flight training is an effective and efficient way to transfer conceptual and declarative knowledge and can enhance flight performance [45]. Moreover, VR-based flight simulators serve as an additional tool for hands-on training of aviation pilots and can achieve significant training outcomes. For this, the comparative research of VR-based flight training with conventional flight training is necessary. As mentioned earlier, a study by Oberhauser [44] also refers to this. Kakkos et al., in their research [46], compared VR to a 2D flight simulation interface to estimate workload based on neurophysiological terms but did not study flight performance. Differences in both interfaces were measured; however, their effect on flight performance could not be determined.

Additionally, the systematic review by van Weelden et al. demonstrated contradicting findings about the relationship between the level of simulation fidelity and workload [47]. Few studies were also done to establish a relationship between pilot performance and a sense of presence in VR. Literature suggests that VR environments achieve a higher sense of presence, improving user learning skills and performance. For validation in VR flight simulations, Evy van Weelden performed a within-subject experiment in which user flight performance and subjective measures such as workload, presence, and engagement were compared in two environments, i.e., Desktop and VR [48]. The research was aimed at studying user performance in immersive VR Vs. Non-immersive environments, user experience, and how it affects flight performance. Results indicated a higher sense of presence and engagement in the VR environment. As VR technology advances, a single strong conclusion is yet to be made about the efficacy of VR-based flight simulation compared to conventional flight training. Therefore, the study on VR-based flight simulation remains a living dialogue while offering big research potential in areas such as the efficacy of VR in terms of workload, user performance evaluation, and situational awareness in a flight simulation.

CHAPTER 3

METHODOLOGY

3.1 Experimental Design

The primary objective of the experiment is to conduct a comparative analysis of pilot performance in two distinct flight environments: Virtual Reality Flight Simulator (VRFS) and Desktop Simulator (DS) within a dynamic flight environment. To achieve this, a well-designed and controlled experimental setup was created for both environments. The overall sequence of the experiment is standardized and identical for both the VRFS and DS scenarios, ensuring consistency in the data collection and evaluation process. The research done for this study follows a systematic and well-structured approach, as illustrated in Figure 19.

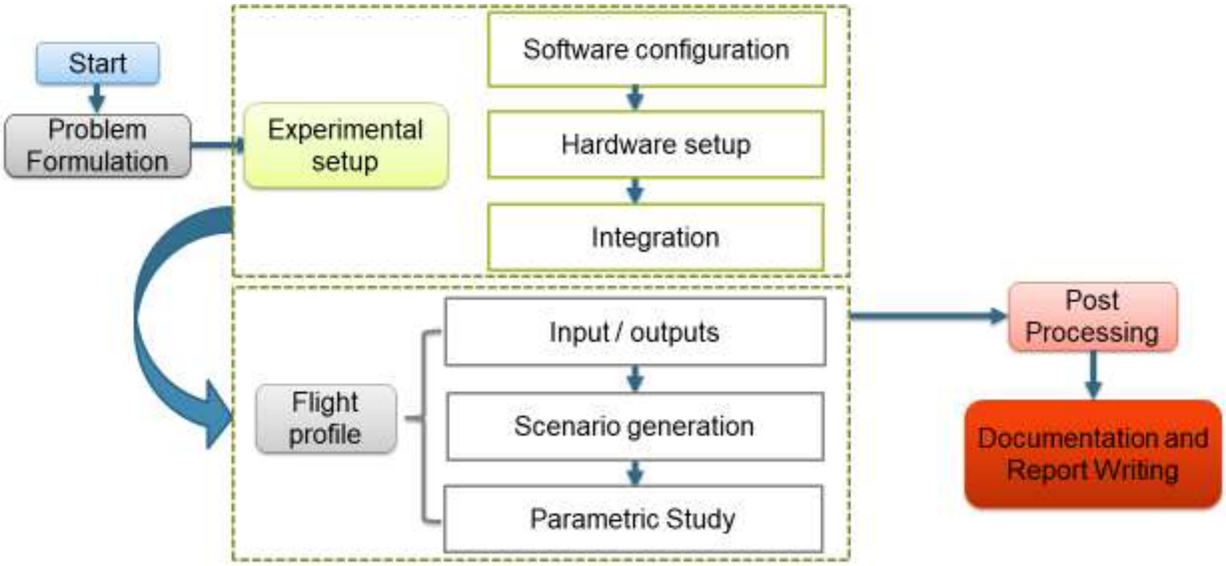

Figure 19: Schematic layout for research

3.2 Apparatus

Different hardware and software components were used to experiment for both test environments, i.e., VRFS and DS as shown in Figure 20. The details of this apparatus are as follows: -

Head Mounted Display (HMD): The HMD used in this setup is the HTC VIVE Pro 2, which provides a 60-degree diagonal field of view (FOV) and a resolution of 1280x1024 pixels for each eye. The HMD allows the user to view the 3D visual scene and provides an immersive experience. By using the continuous tracking input, a 3D visual scene is rendered for the eyes of the user. The detailed technical specifications of the HMD are given in Table 2:

Feature	Specification
Resolution	2448 × 2448 pixels (per eye)
Refresh Rate	90 /120 Hz
Field of View	120 deg (Horizontal)
IPD	Adjustable
Audio	Hi-Res Audio-certified headphones
Tracking	02 external base stations for SteamVR Tracking 2.0
Connectivity	DisplayPort 1.2 and a USB 3.0

Table 2: Technical specifications of HTC Vive Pro2

Processor PC: The processor PC is responsible for computing and rendering the 3D visual scene based on the user's inputs and interactions. It is a crucial component to ensure smooth and realistic simulation.

HOTAS (Hands-on Throttle and Stick): The Rhino HOTAS controls the flight simulator, allowing the user to control the virtual aircraft's throttle and stick movements. This enhances the simulation's realism and immersion.

Flight Simulation Software (Xplane-12): Xplane-12 is the flight simulation software used in this setup. It integrates all the hardware elements and provides a 3D virtual environment for the user to fly the aircraft. It also offers the option to switch between desktop and VR mode, allowing users to experience the simulator in different setups.

Display Screen: Besides the VR mode, the setup includes a desktop simulator configuration. This configuration utilizes three display screens to create a 180-degree field of view for the pilot, enhancing immersion and realism when using the flight simulator without the VR headset.

Figure 20: Apparatus for VR setup

3.3 Participants

Five experienced pilots participated in this experiment, each with an average of 1700 flying hours. The pilots had a mean age of 28.6 years, with the youngest pilot being 24 years old and the oldest pilot being 31 years old. All participants had experience with Virtual Reality (VR) in other domains, as shown in Figure 22, while only 2 out 5 (40 percent) participants had previous experience with VR-based flight simulation. Notably, one user had an eyesight issue and performed the flight simulation while wearing spectacles. However, this visual impairment did not adversely affect the efficacy of the experimental setup, as the pilot could participate in the study and complete the required tasks fully.

By including pilots with considerable flight experience and a range of ages, the experiment aimed to evaluate the effectiveness of the VR-based flight simulation in a diverse and representative sample. Despite the participants' familiarity with VR in other domains, their lack of experience in VR-based flight simulation ensured that the study could assess the impact of this specific context on their performance and perceptions. The presence of one pilot with visual correction needs, using spectacles, highlights the flexibility and accessibility of the experimental setup, accommodating users with varying visual requirements without compromising the validity of the results.

Overall, the diverse and experienced participant group ensured that the study's findings could be more broadly applicable to pilots with varied backgrounds and expertise, providing valuable insights into the potential benefits and challenges of using VR-based flight simulation for training and evaluation purposes.

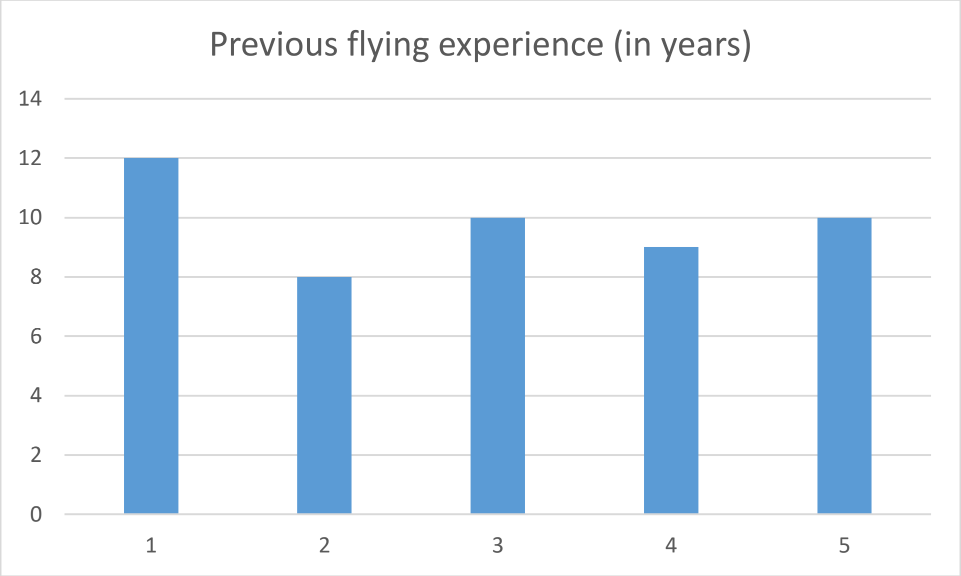

Figure 21: Flying experience of pilots

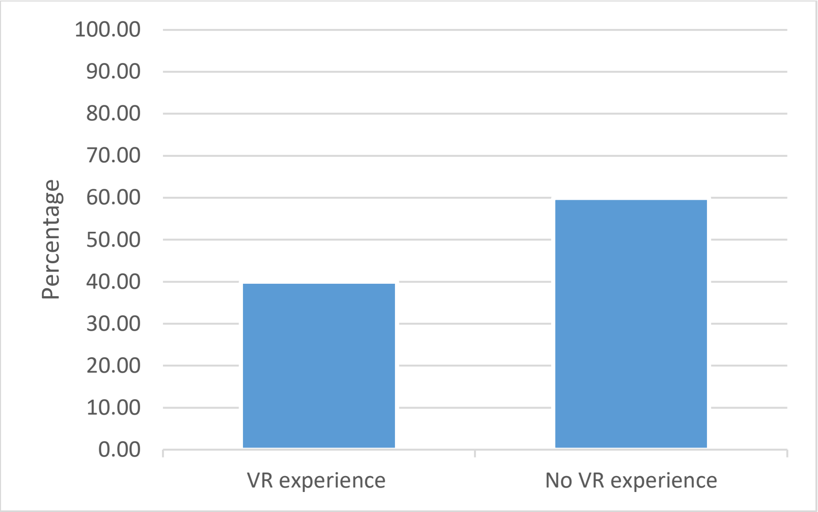

Figure 22: Previous experience of pilots with VR flight simulator

3.4 Scenario

The study developed two scenarios using Xplane12 to assess flight performance in different dynamic environments. The first scenario represented clear weather conditions and normal flying circumstances. In contrast, the second scenario was designed to simulate low visibility conditions and included varying wind conditions. Before commencing the main experiments, all participants underwent a familiarization session where they flew a left-hand traffic pattern using the software interface and the Virtual Reality (VR) headset. This allowed them to become acquainted with the flight simulator setup. The traffic pattern is shown in Figure 23.

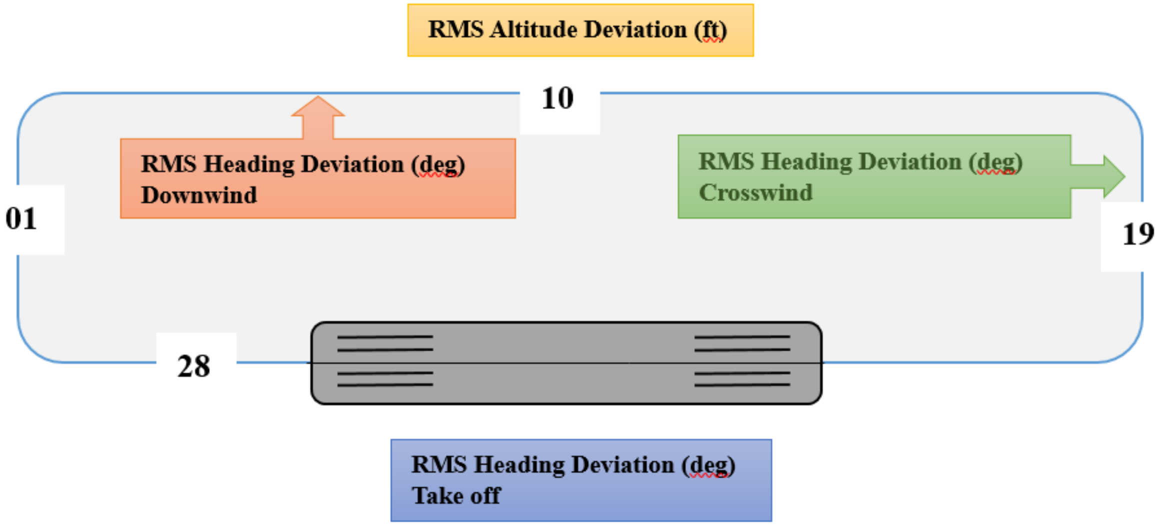

Figure 23: Left-hand traffic pattern for experiment

Scenario 1 began with a take-off from Runway 28 at Portland Airport. Participants were required to fly a left-hand traffic pattern at 1000 feet during this scenario. Throughout the circuit, they were instructed to consistently maintain the desired altitude and corresponding heading in all pattern phases. After completing the left-hand pattern, the participants landed the aircraft.

Following Scenario 1, the participants progressed to Scenario 2, where they were again tasked with flying a left-hand traffic pattern. In this scenario, they were required to execute a full-stop landing. The primary objective remained to maintain the desired altitude and heading during all pattern phases.

Both scenarios were conducted twice for each participant, using the Virtual Reality (VR) flight simulator setup with the Head-Mounted Display (HMD) and once using the desktop simulator with the projected outside visual. The order of simulation environments was counterbalanced among the participants to mitigate any potential bias or artifacts. Some participants started with the VR simulation, while others began with the desktop simulator. Figures 24 & 25 show a participant pilot performing the test experiment in a Desktop and VR environment, respectively.

By conducting the experiments in this manner, the study aimed to comprehensively evaluate the pilots' performance in both simulation environments, ensuring a robust and reliable assessment of their flight abilities in varied conditions. VR technology and desktop simulation allowed for a comprehensive comparison of the participants' performance, providing valuable insights into each setup's potential benefits and challenges.

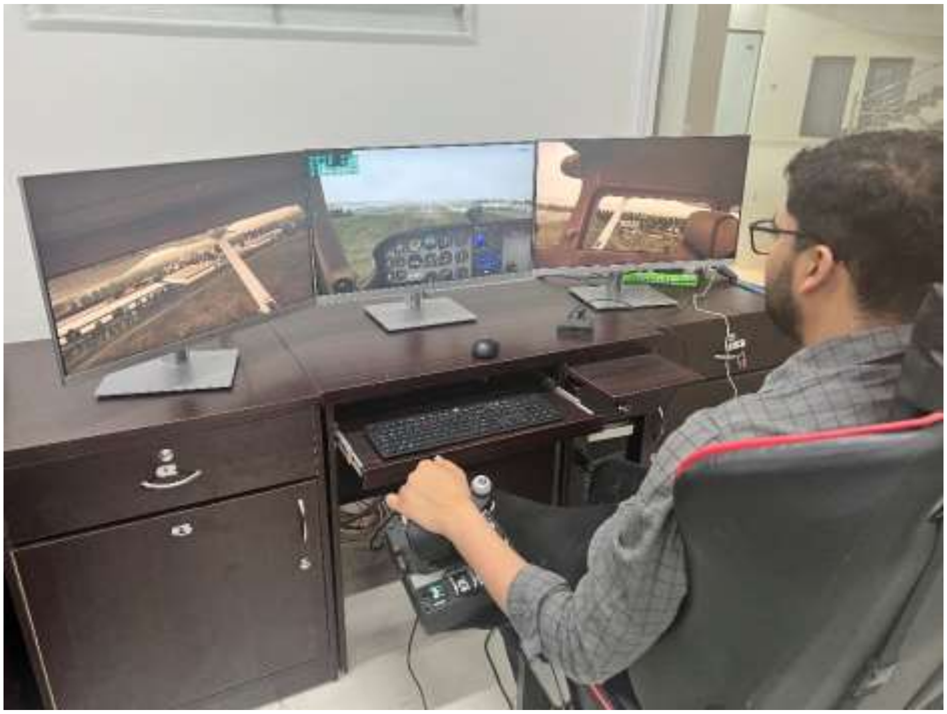

Figure 24: Participant flying in the Desktop environment

Figure 25: Participant flying in VR environment

3.5 Data Collection

The traffic pattern was methodically divided into distinct flight segments to ensure precise interpretation and facilitate practical data analysis. Figure 23 visually depicts the traffic pattern and the corresponding dependent measurements used in the evaluation process. Various dependent measures were utilized to validate the collected data and evaluate each pilot's performance based on the data acquired. Data for all performance parameters were collected from each participant for each scenario.

Following data collection, the next step involved organizing the data by categorizing it on a scenario-by-scenario basis and extracting the necessary parameters. Each pilot's data was further segregated according to individual flight segments and further recorded in Microsoft Excel sheets.

The Root Mean Square (RMS) value for each measured parameter was calculated to analyze the data quantitatively. The RMS value measures the overall deviation or error in the data, which aids in understanding the pilot's performance with greater precision. Furthermore, all deviations were quantified in RMS values, enabling uniformity and consistency in the analysis across various parameters and scenarios. Statistical analysis tools were then applied to assess the performance of the pilots in each scenario and test environment.

This systematic approach to data analysis allowed for the comprehensive evaluation of each pilot's performance across different flight segments and scenarios. By using RMS values and statistical techniques, an effort was made to draw meaningful conclusions from the data, identify patterns, and assess the efficacy of each pilot's actions during the experiments. Using data analysis tools such as Minitab and MS Excel enhanced the objectivity and rigor of the study, enabling a robust assessment of the pilots' performance in various test conditions.

3.5.1 Heading Deviation (degrees)

During the evaluation process, the parameter under consideration was measured for specific phases of the flight, including take-off and go-around, the crosswind leg, and the downwind leg. Participants were given explicit instructions to select the appropriate heading during each trial. They were provided a thorough briefing to maintain this heading as accurately as possible throughout the respective flight segments. The data collected during these trials were then utilized to analyze the participants' performance and adherence to the prescribed headings, contributing to a comprehensive assessment of their piloting skills in relation to the given flight scenarios.

3.5.2 Altitude Deviation (feet)

The specific parameter under consideration was measured when the pilot gained the target altitude of 2,000 feet. The participants were instructed to maintain this recorded altitude value during this specified flight period. By monitoring the pilot's performance in maintaining the specified altitude within the designated flight segment, valuable data was collected and analyzed to assess their skill and precision in altitude control during the flight.

3.5.3 Workload

After each experiment, in addition to collecting flight data, the NASA-Task Load Index (NASA-TLX) was used to assess the amount of work the pilots had to do. Using this, all the pilots scored their mental, physical, and temporal demands, effort, and performance on a scale ranging from -5 to +5 (extremely low to very high). This assessment provided valuable insights into the cognitive and physical demands imposed on the pilots during the experiments. A post-virtual reality questionnaire was also developed to collect data on the reliability and validity of the experiment's design. Throughout the experimentation phase, each pilot participated in four different scenarios, and after each scenario, they provided four responses to the NASA TLX and SSQ. Additionally, one post-VR response was collected from each pilot, resulting in 25 responses being gathered.

This meticulous data collection allowed for a comprehensive evaluation of the pilots' experiences, workload, and flight performance, thereby providing a robust basis for analyzing and drawing conclusions from the experiments. The combination of objective flight data, subjective assessments through questionnaires, and post-VR feedback helped ensure the thoroughness and validity of the research study.

CHAPTER 4

RESULTS & DISCUSSION

4.1 Hypothesis

This chapter presents the results of the comparative analysis between Virtual Reality (VR) and Desktop Flight Simulators. The analysis focuses on various aspects, including immersion and realism, user experience, training effectiveness, and simulator performance. The aim is to determine the strengths and weaknesses of each simulator type and provide insights into their respective capabilities for flight training. After requisite data collection and sorting, Analysis of Variance (ANOVA) was applied to the results to find significant differences between two sets of values. To apply ANOVA, a hypothesis was formulated that the mean of the measured values (deviations) would remain the same for both test conditions. The alternate hypothesis states that all means are not equal. Alpha was set to be 0.05.

Null hypothesis	All means are equal.
Alternative hypothesis	Not all means are equal.
Significance level	$\alpha = 0.05$
S1	Scenario 1
S2	Scenario 2
S1-V	Scenario 1 in VR env.
S2-V	Scenario 2 in VR env.
S1-D	Scenario 1 in Desktop env.
S2-D	Scenario 2 in Desktop env.

4.2 Results

Using the collected flight data, two types of comparisons were performed, i.e., test environment-wise (VR and Desktop) and scenario-wise (S1 and S2). In the first type, a comparison was made for VR and desktop environments while keeping the scenario constant. The second type follows the converse sequence with a scenario-wise comparison and a constant test environment. Results for both types of comparisons are tabulated in the same sequence. The parametric data deviations for VR vs. Desktop for Scenario 1 are presented descriptively in Table 3. It can be seen that the error for the RMS heading is lesser in VR than in the desktop scenario. However, when ANOVA was applied to measure the difference between the two conditions, it was found that the difference was not significant in all three legs of the traffic pattern. [(Take-off - F=1.23, p=0.300), (Crosswind-F=1.58, p=0.244), (Downwind- F=3.113, p=0.115)]. The same pattern was observed for Altitude deviation, showing less deviation value for VR than Desktop (F=3.39, p=0.103). The consolidated boxplot of RMS heading deviation for all three legs of the traffic pattern for Scenario 1 is shown in Figure 26. It can be seen that deviation for all three legs of the traffic pattern, deviation for VR environment is lesser than Desktop. Similarly, the boxplot for altitude deviation for Scenario 1 is shown in Figure 27, which shows a lesser deviation for VR compared to the desktop environment.

						95 % confidence interval	
Dependent measure	**Environment**	**Mean**	**Std. error**	**F value**	**P value**	**Lower bound**	**Upper bound**
RMS Heading Take off	VR	4.306	0.582	1.23	0.300	2.987	5.625
	Desktop	5.203	0.562			3.884	6.522
RMS Heading Crosswind	VR	7.218	0.600	1.58	0.244	5.831	8.604
	Desktop	8.287	0.603			6.901	9.674
RMS Heading Downwind	VR	5.673	0.320	3.113	0.115	4.951	6.395
	Desktop	6.456	0.306			5.734	7.178
RMS Altitude deviation	VR	78.86	4.01	3.39	0.103	68.15	89.21
	Desktop	80.25	5.06			69.73	90.78

Table 3: Summary of Flight parameters deviation for Scenario 1 (VR vs. Desktop)

In Scenario 1, participants were **14.8%** better at maintaining their desired heading and **7%** better at maintaining their desired altitude in VR.

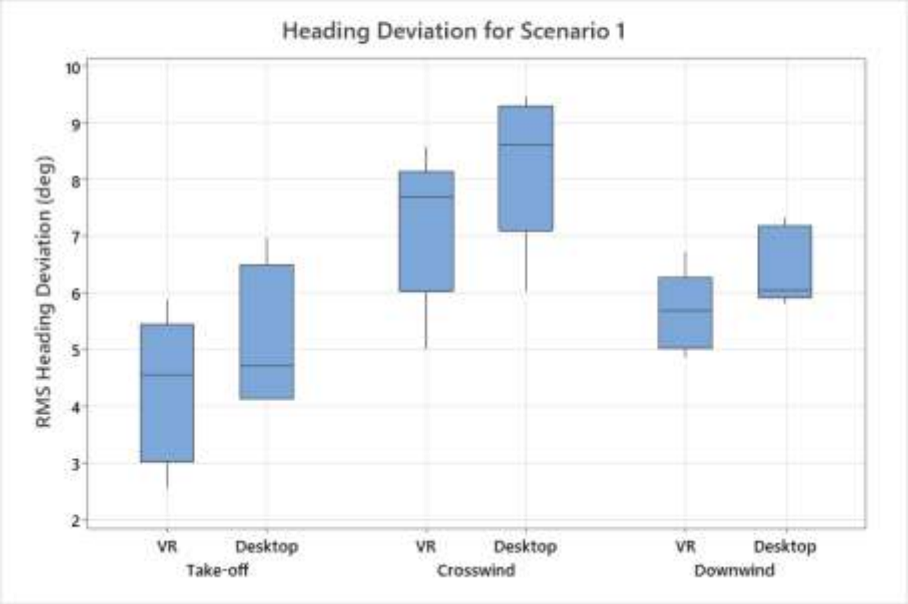

Figure 26: Box plot of RMS heading deviation for Scenario 1 (VR vs. Desktop)

Figure 27: Box plot of RMS Altitude deviation for Scenario 1 (VR vs. Desktop)

The flight data was again compared for scenario 2 in both test environments (VR vs. Desktop), and less deviation in flight data was found. However, ANOVA showed significant differences between the two conditions [(Take-off - F=2.33, p=0.165), (Crosswind-F=14.27, p=0.005), (Downwind- F=7.87, p=0.023]. Similar results were found for altitude deviation, with VR having lesser deviation than the desktop environment (F=5.89, p=9.26). The summary of results data for Scenario 2 is shown in Table 4.

						95 % confidence interval	
Dependent measure	**Environment**	**Mean**	**Std error**	**F value**	**P value**	**Lower bound**	**Upper bound**
RMS Heading Take off	VR	8.054	0.442	2.33	0.165	6.230	9.878
	Desktop	9.76	1.03			7.94	11.59
RMS Heading Crosswind	VR	9.432	0.739	14.27	0.005	7.645	11.399
	Desktop	13.990	0.954			12.023	15.957
RMS Heading Downwind	VR	10.472	0.816	7.87	0.023	8.272	12.673
	Desktop	14.26	1.08			12.06	16.46
RMS Altitude deviation	VR	97.48	5.89	5.89	0.041	79.58	115.38
	Desktop	124.11	9.26			106.21	142.02

Table 4: Summary of Flight parameters deviation for Scenario 2 (VR vs. Desktop)

The consolidated boxplot of RMS heading deviation for all three legs of the traffic pattern for Scenario 2 is shown in Figure 28. It can be seen that the deviation for all three legs of the traffic pattern for the VR environment is lesser than for the Desktop. Similarly, the boxplot for altitude deviation for Scenario 2 is shown in Figure 29, which shows a lesser deviation for VR compared to the desktop environment. In Scenario 2, participants were **25.7%** better at maintaining their desired heading and **24%** better at maintaining their desired altitude in VR. These results suggest that participants generally performed better in maintaining their desired flight parameters, i.e., heading and altitude, in the VR environment compared to the desktop simulator, with more considerable improvements seen in Scenario 2.

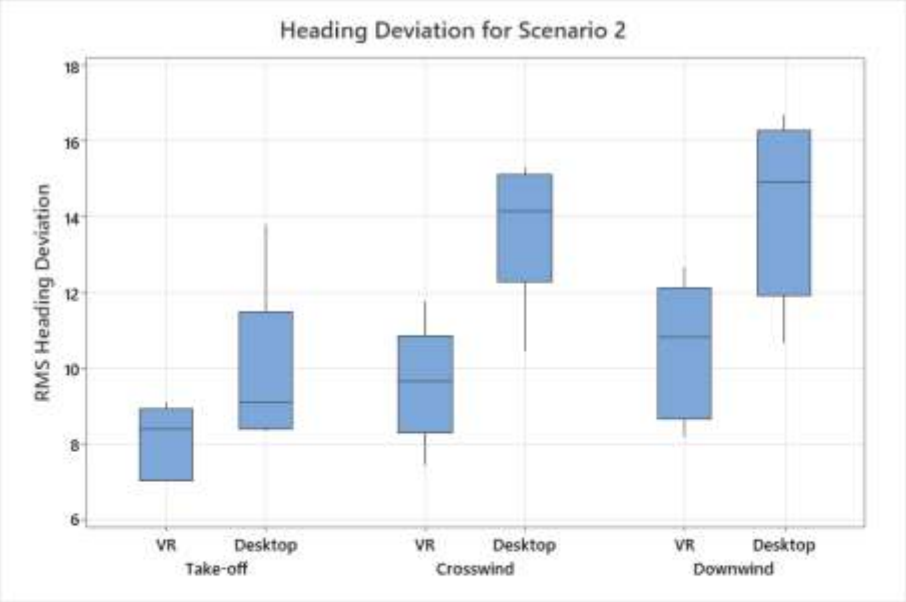

Figure 28: Box plot of RMS heading deviation for Scenario 2 (VR vs. Desktop)

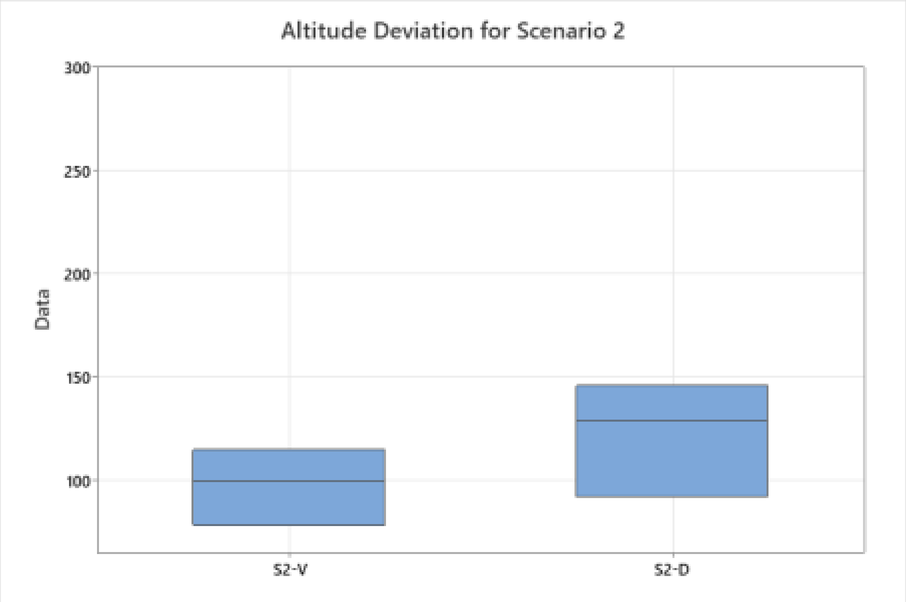

Figure 29: Box plot of RMS Altitude deviation for Scenario 2 (VR vs. Desktop)

The second type of comparison was based upon the scenario effect as both scenarios had different weather conditions; therefore, the study was done to measure the effect of difficulty level in both test environments. The summary of flight data for scenario 1 vs. scenario 2 for the VR environment is shown in Table 5. It can be seen that the deviation for flight data was lesser in scenario 1 as compared to scenario 2 [Heading deviation (Take-off - F=26.31, p=0.001), (Crosswind-F=5.41, p=0.048), (Downwind- F=30.01, p=0.001].

Similar results were found for altitude deviation, with scenario 1 having lesser deviation than scenario 2 (F=17.31, p=0.030).

SCENARIO 1 vs. SCENARIO 2 (VR)

						95 % confidence interval	
Dependent measure	**Scenario**	**Mean**	**Std. error**	**F value**	**P value**	**Lower bound**	**Upper bound**
RMS Heading Take off	S1	4.306	0.582	26.31	0.001	3.115	5.498
	S2	8.054	0.442			6.863	9.246
RMS Heading Crosswind	S1	7.218	0.600	5.41	0.048	5.666	8.769
	S2	9.432	0.739			7.880	10.984
RMS Heading Downwind	S1	5.673	0.320	30.01	0.001	4.244	7.0101
	S2	10.472	0.816			9.044	11.901
RMS Altitude deviation	S1	78.68	4.01	17.31	0.030	79.58	115.38
	S2	97.48	5.89			106.21	142.02

Table 5: Summary of Flight parameters deviation for VR environment (S1 vs. S2)

The consolidated boxplot of RMS heading deviation for the VR environment for all three legs of the traffic pattern is shown in Figure 30. It can be seen that the deviation for all three legs of the traffic pattern for the VR environment is lesser than for the Desktop. Similarly, the boxplot for altitude deviation for the VR environment is shown in Figure 31, which shows a lesser deviation for VR compared to the desktop environment.

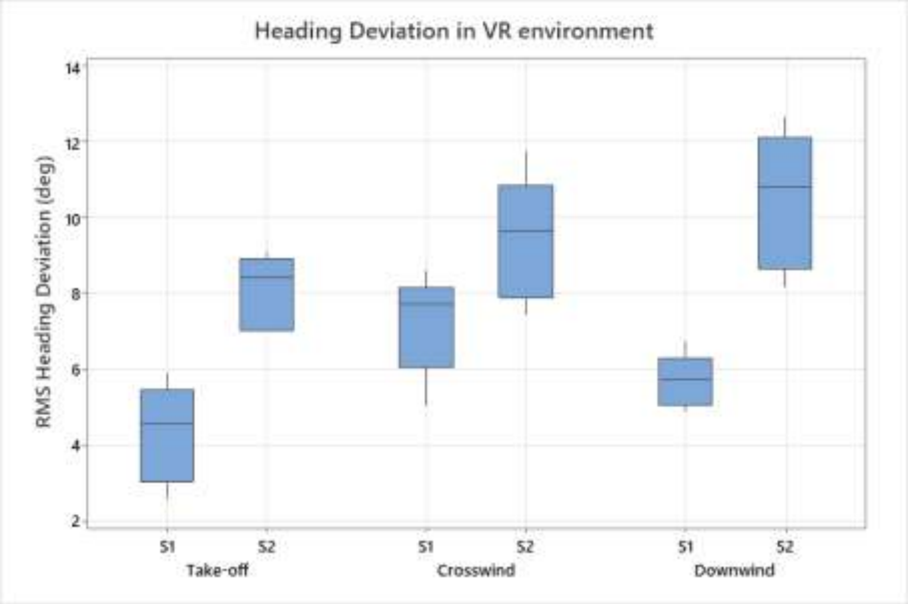

Figure 30: Box plot of RMS heading deviation in VR environment (S1 and S2)

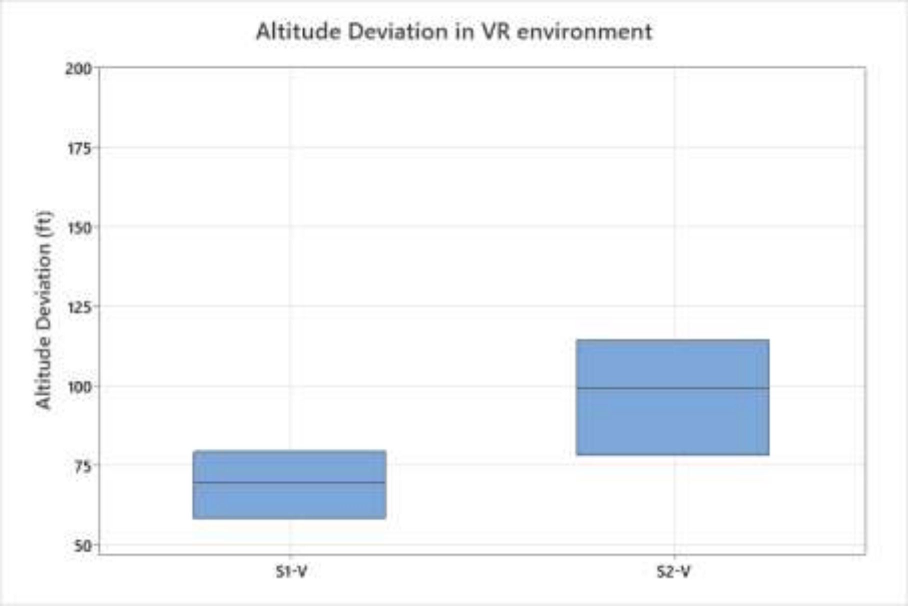

Figure 31: Box plot of RMS Altitude deviation in VR environment (S1 and S2)

The summary of scenario-wise comparison for the desktop environment is shown in Table 6. There was a significant difference observed between the two scenarios for heading deviation, as seen by ANOVA results [(Take-off - F=15.16, p=0.005), (Crosswind-F=25.54, p=0.001), (Downwind- F=48.70, p=0.00001]. The deviation for scenario 1 was lesser than scenario 2 in the desktop environment for both heading and altitude.

						95 % confidence interval	
Dependent measure	**Environment**	**Mean**	**Std error**	**F value**	**P value**	**Lower bound**	**Upper bound**
RMS Heading Take off	S1	5.203	0.562	15.16	0.005	3.293	7.113
	S2	9.76	1.03			7.85	11.67
RMS Heading Crosswind	S1	8.287	0.603	25.54	0.001	6.448	10.127
	S2	13.99	0.954			12.150	15.380
RMS Heading Downwind	S1	6.456	0.306	48.70	0.00001	4.633	8.279
	S2	14.26	1.08			12.43	16.08
RMS Altitude deviation	S1	80.25	5.06	17.28	0.003	63.04	97.46
	S2	124.11	9.26			106.91	141.32

Table 6: Summary of Flight parameters deviation for the Desktop environment (S1 vs. S2)

The consolidated boxplot of RMS heading deviation for all three legs of the traffic pattern for the Desktop environment is shown in Figure 32. It can be seen that deviation for all three legs of the traffic pattern, deviation for VR environment is lesser than Desktop. Similarly, the boxplot for altitude deviation for Scenario 1 is shown in Figure 33, which shows a lesser deviation for VR compared to the desktop environment.

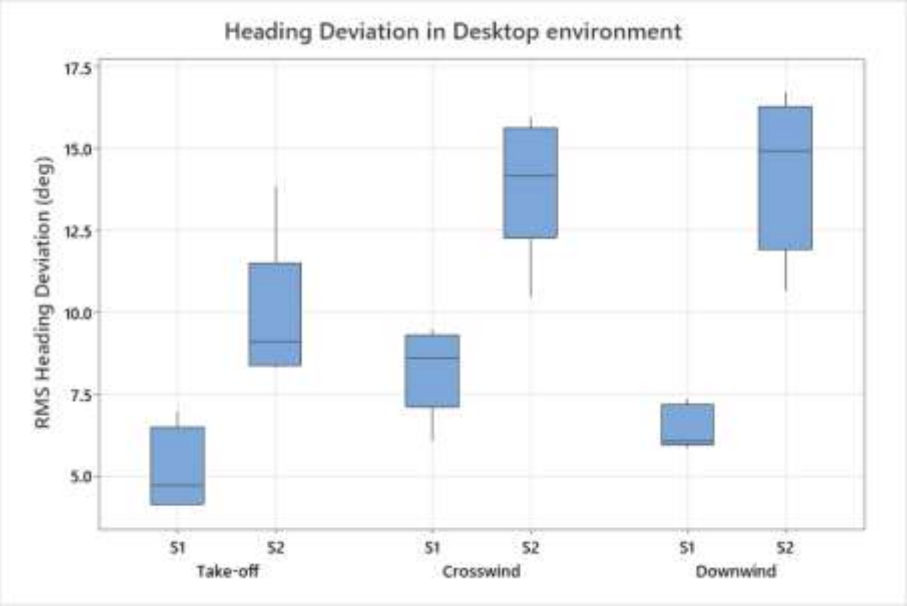

Figure 32: Box plot of RMS heading deviation in the Desktop environment (S1 and S2)

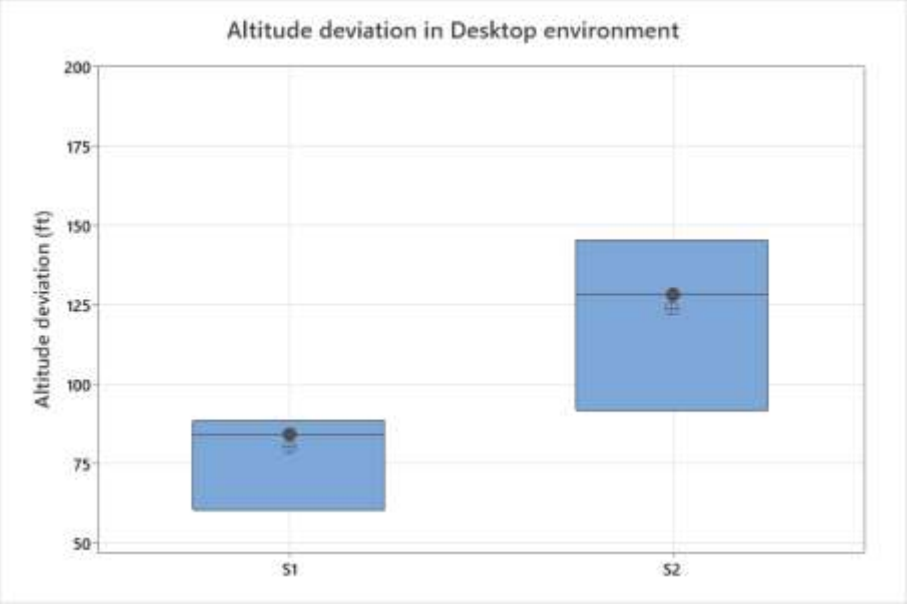

Figure 33: Box plot of RMS Altitude deviation in the Desktop environment (S1 and S2)

4.2.1 Heading Deviation (Degrees)

The individual results for ANOVA performed on Heading deviation in the three legs of the traffic pattern (take-off, crosswind, downwind) for scenario-wise and test environment-wise (VR vs. Desktop) were calculated and are shown collectively in Figure 34 and Figure 35. It is evident from figures that deviations for the VR test environment are greater than the desktop environment which validates the findings of the research. Similarly, the deviations for S2 are greater than S1 in both VR and desktop environments which shows the negative effect of task difficulty on flight performance.

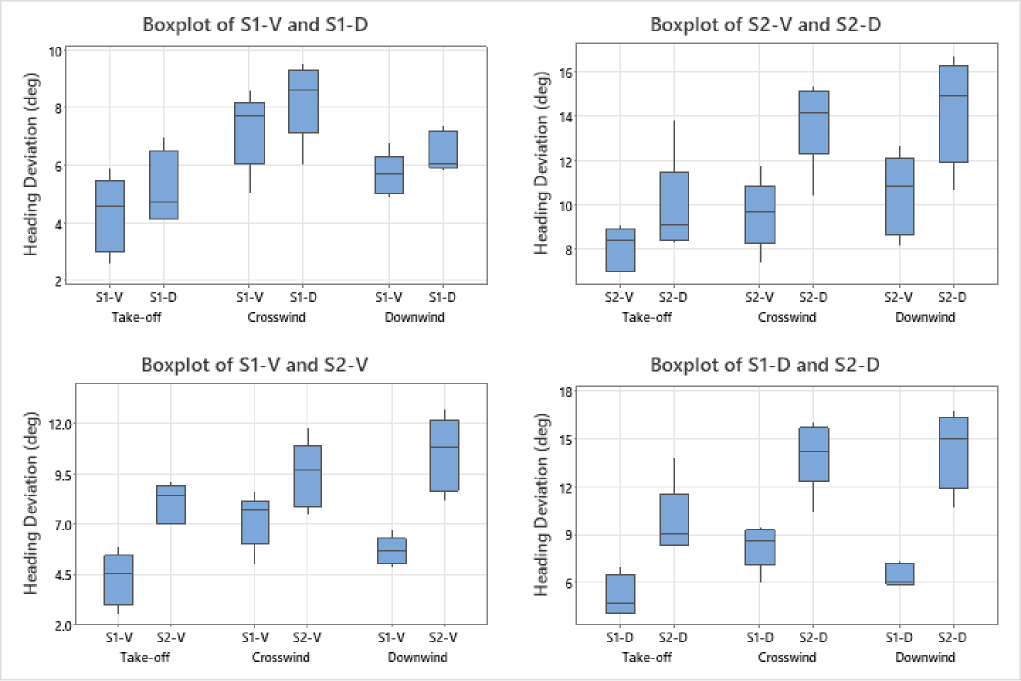

Figure 34 : Boxplot of Heading Deviation (deg)

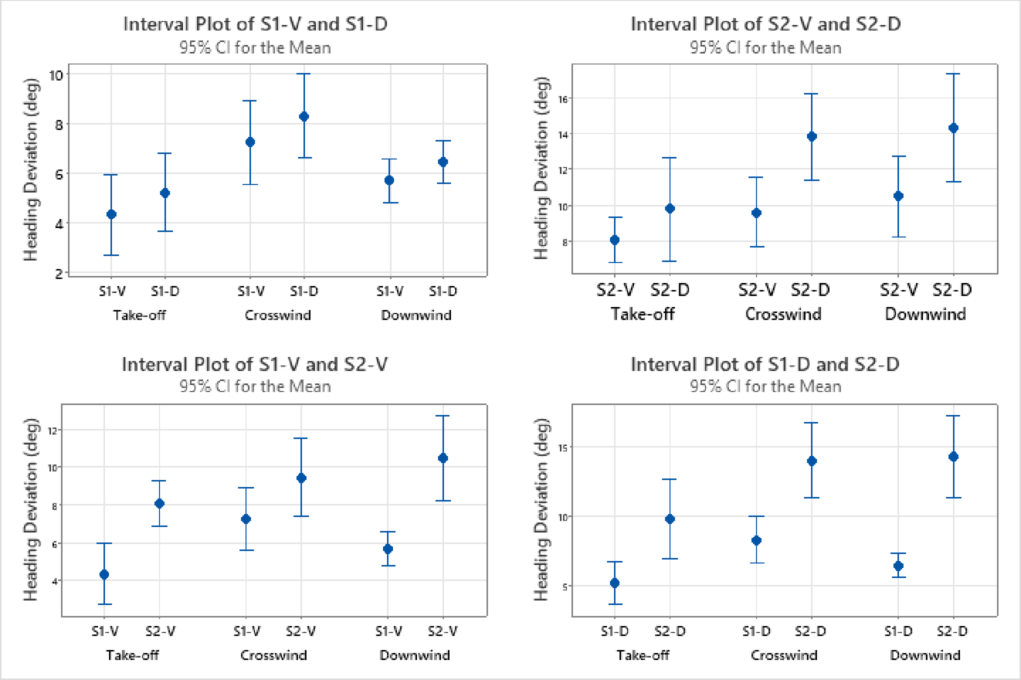

Figure 35 : Interval plot of Heading Deviation (deg)

4.2.2 Altitude Deviation (feet)

The results for ANOVA performed on Altitude deviation for all types of comparisons were calculated and are shown collectively in Figure 36 and Figure 37. For scenario-wise comparison, the deviations for S1-D and S2-D are greater than S1-V and S1-D respectively exhibiting better performance in VR test environment. For scenario-wise comparison, the deviations for S2 are greater than S1 in both test environments (VR and desktop) showing the effect of task difficulty on flight performance.

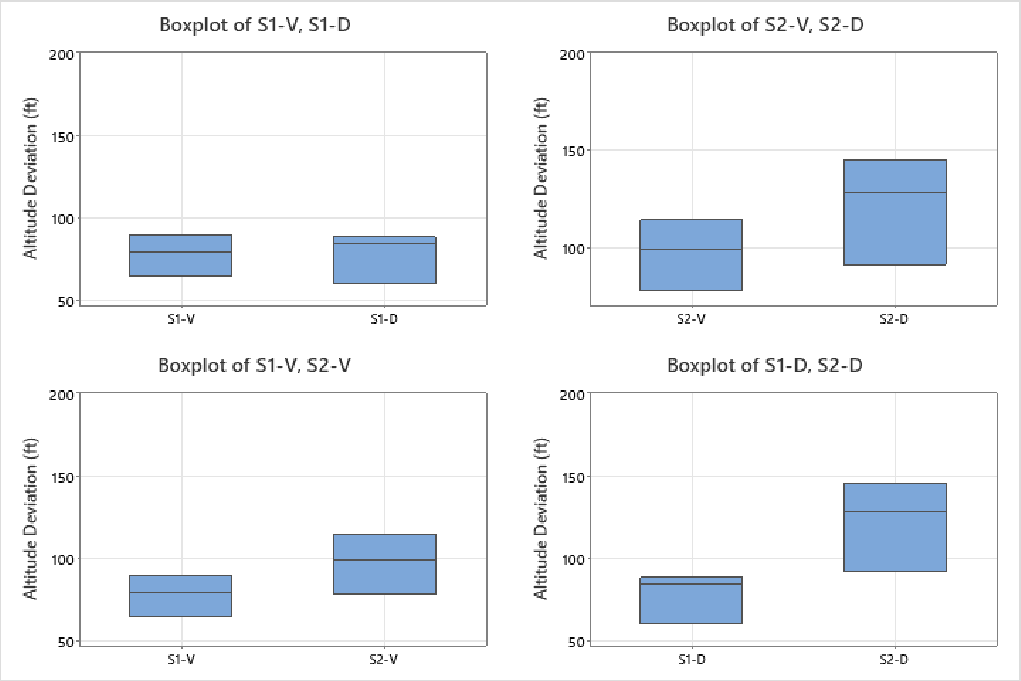

Figure 36 : Boxplot of Altitude Deviation (ft)

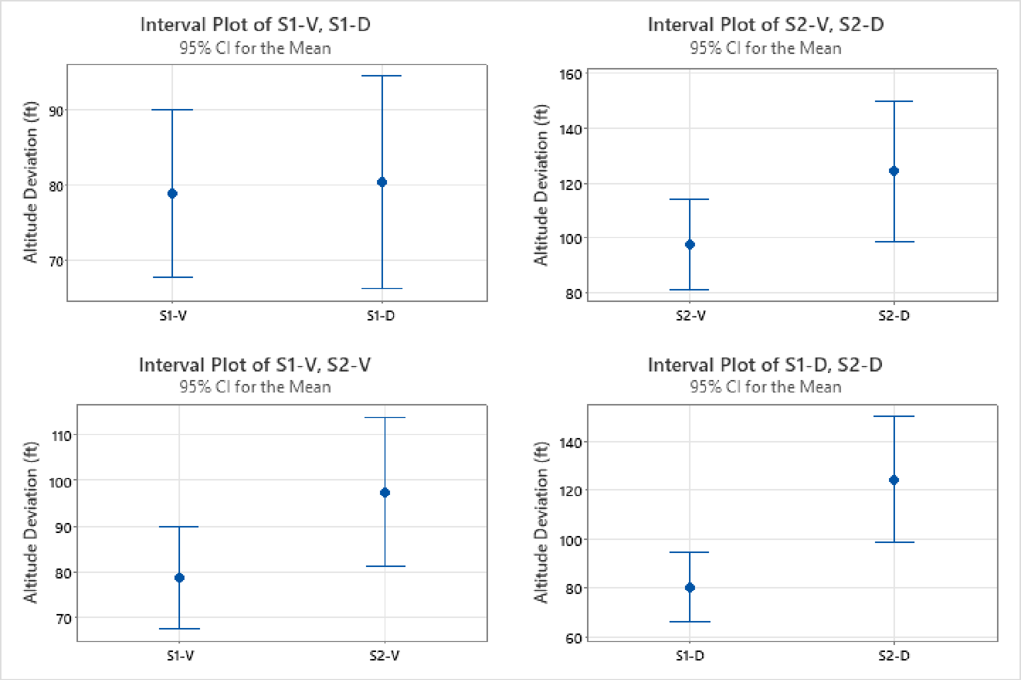

Figure 37: Interval plot for Altitude Deviation (ft

4.2.3 Workload

NASA TLX index was used to calculate workload after the pilots performed each test condition. Test environment-wise comparison was performed to assess the workload against both scenarios. For both scenarios (S1 and S2), results showed greater workload in the VR environment as compared to the desktop environment. When ANOVA was applied to measure the difference between the two conditions, it was found that the difference was significant for scenario 1 [F=21.99, p=0.003) as well as scenario 2 (F=17.62, p=0.244). The consolidated result of workload for Scenario 1 and Scenario 2 in both environments is shown in Figure 38. Results depict greater workload in the VR environment i.e., 44 % more for scenario 1 and 28 % more for scenario 2 as compared to desktop environment.

						95 % confidence interval	
Scenario	**Environment**	**Mean**	**Std. error**	**F value**	**P value**	**Lower bound**	**Upper bound**
Scenario 1	VR	54.46	3.10	21.99	0.002	47.62	61.31
	Desktop	34.77	2.83			27.92	41.62
Scenario 2	VR	69.66	3.05	17.62	0.003	63.01	76.32
	Desktop	52.53	2.71			45.88	59.19

Table 7 : Summary of Workload score for test environment-wise comparison

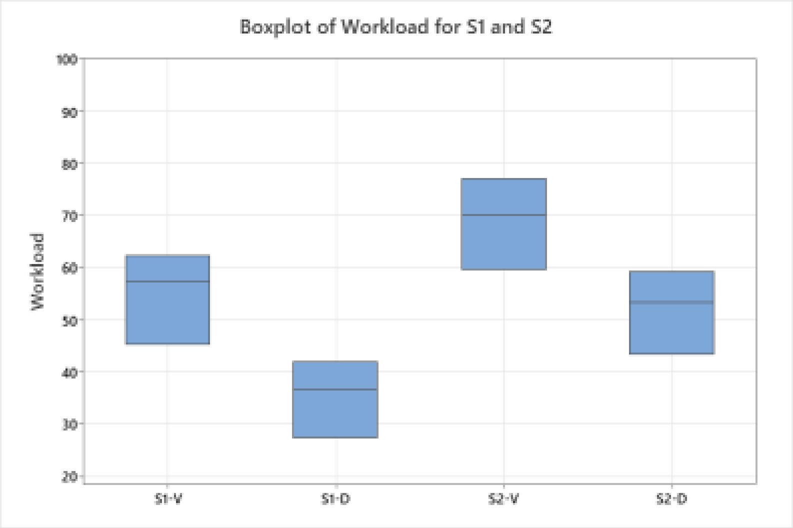

Figure 38: Workload comparison based on test environment

The score of NASA TLX was also analyzed to examine the effect of task difficulty on workload level. For this purpose, a scenario-wise comparison was performed for both test environments. When ANOVA was applied to measure the difference between the two conditions, it was found that the difference was not significant was significant for VR environment (F=12.21, p=0.008) as well se desktop environment (F=20.53, p=0.002) as shown in Table 8. Difference between the two scenarios showed a more significant workload in Scenario 2 compared to Scenario 1 i.e., 24.5 % more in the VR environment, and 40.7 % more in the desktop environment as shown in Figure 39.

						95 % confidence interval	
Test Environment	**Scenario**	**Mean**	**Std. error**	**F value**	**P value**	**Lower bound**	**Upper bound**
VR	S1	54.46	3.10	12.21	0.008	47.37	61.56
	S2	69.66	3.05			62.57	76.75
Desktop	S1	34.77	2.83	20.53	0.002	28.37	41.16
	S2	52.53	2.71			46.14	58.93

Table 8 : Summary of Workload score for Scenario wise comparison

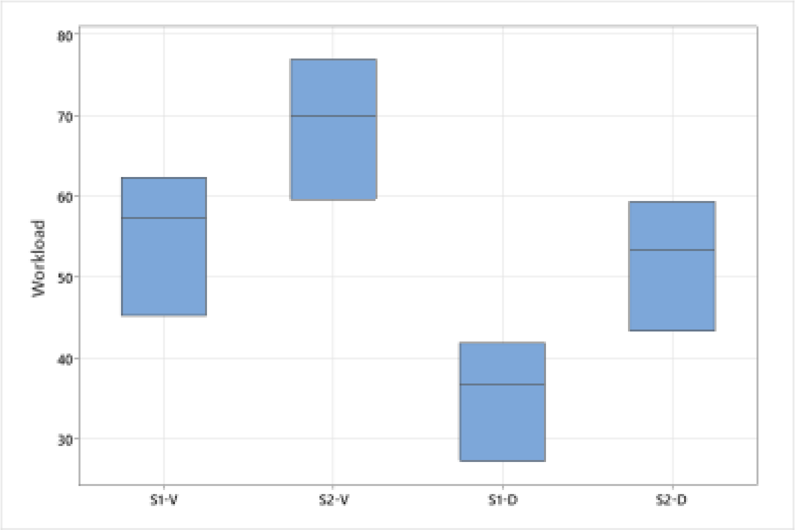

Figure 39: Workload comparison based on task difficulty

4.2.4 Visual Immersion

The VR flight simulator demonstrated superior visual immersion compared to the desktop simulator. Participants reported a heightened sense of presence and engagement in the virtual environment. The VR headset's ability to provide a wide field of view and depth perception contributed significantly to this immersive experience. In contrast, the desktop simulator's screen display lacked the same level of immersion as the participants were aware of their surroundings and often felt disconnected from the flying experience. Participants’ feedback on realism of both types of simulators is shown in Figure 40.

While the VR simulator excelled in visual immersion, some participants experienced discomfort, particularly during complex maneuvers or sudden movements. The desktop simulator, grounded in a traditional setup, did not induce these discomforts. However, this came at the cost of diminished physical realism, as participants did not experience the same sense of movement as they did in the VR environment.

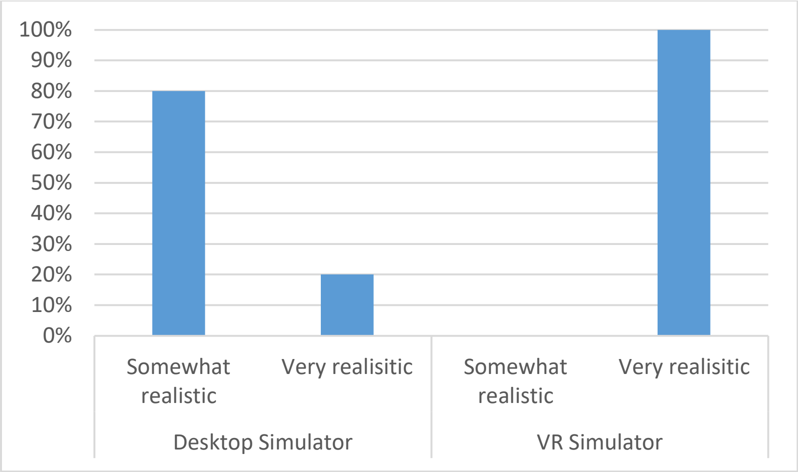

Figure 40: User feedback on the realism of the flight simulator

4.2.5 Training Effectiveness

Both simulators showed potential for skill acquisition. The desktop simulator was equally effective for basic flight procedures and clear weather flying. The VR simulator, however, demonstrated superiority in flying adverse weather scenarios due to better graphics and visual fidelity, a heightened level of immersion, and spatial awareness. Participants reported a greater sense of "being there," leading to better decision-making and retention of procedures.

However, some participants reported occasional frame rate drops and motion blur in the VR environment, which detracted from the overall experience. The desktop simulator maintained stable performance throughout, although at the expense of graphical quality. While filling the feedback Performa, all the participants reported better possible training outcomes for the VR flight simulator than the Desktop simulator for routine and dynamic flight scenarios.

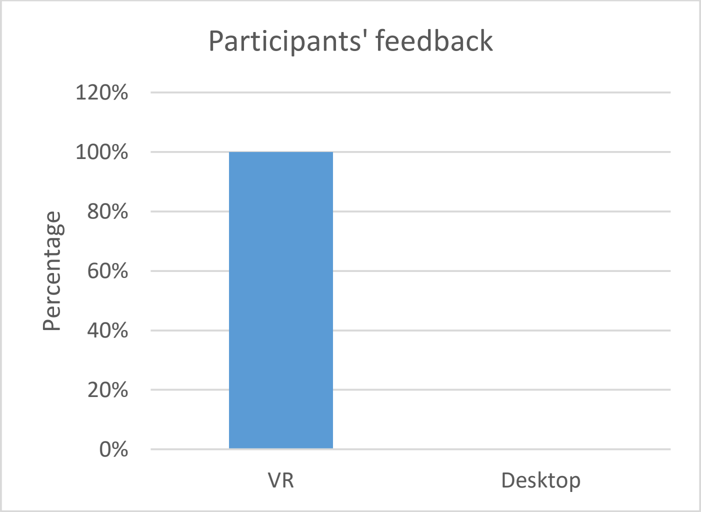

Figure 41: User feedback on preferred flight simulator

CHAPTER 5

CONCLUSION & FUTURE WORK

5.1 Conclusion

This study undertook a comprehensive comparative analysis between Virtual Reality (VR) and Desktop Flight Simulators, focusing on their flight performance capabilities and associated workload. The findings presented in this study shed light on the strengths and limitations of each simulator type, ultimately revealing that VR exhibits superior flight performance capabilities while demanding a higher workload from users. For performing the research study, two scenarios were built to assess pilot performance in both test environments (VR vs. Desktop). Five participants were recruited to perform the experiment. All the participants experienced heightened immersion and realism in the VR environment.

Moreover, there were fewer deviations in flight parameters data in both scenarios for the VR environment, contributing to superior flight performance. This was particularly evident in Scenario 2, involving complex dynamics due to adverse weather conditions. For Scenario 1, the pilot performance in both test environments was relatable. One significant caveat to the superior flight performance of the VR simulator is the increased workload it imposes on users, as the participants reported higher cognitive and physical demands while experimenting in the VR environment. This was attributed to navigating the virtual cockpit and managing the VR headset.

The findings of this study have notable implications for flight training and other domains that utilize simulators. Virtual Reality flight simulators offer a promising avenue for training pilots in different flight situations. The heightened sense of presence and physical interaction in VR can contribute significantly to skill acquisition and decision-making in critical situations. However, increased cognitive workload should be addressed carefully to ensure practical and comfortable training experiences. Ultimately, the choice between VR and Desktop simulators will depend on specific training goals, user preferences, and balancing performance and workload considerations.

5.2 Limitations

One significant limitation of this study is the small number of participants involved. Limiting the number of participants was driven by the substantial amount of subjective feedback collected across various scenarios, which necessitated careful analysis and interpretation. While the statistical analysis conducted on the available data yielded significant results, the small sample size may affect the generalizability of the findings. Future research could involve a more extensive and diverse participant pool to enhance the robustness and applicability of the results.

The study primarily focused on a specific set of scenarios and aircraft types, which may limit the broader applicability of the findings. Including a wider variety of scenarios, environments, and aircraft models would offer a more comprehensive assessment of simulator performance and training outcomes across different contexts. This would provide a more nuanced understanding of the strengths and limitations of VR and Desktop simulators in diverse flight scenarios.

5.3 Future Work

Future research should explore dynamic situations incorporating more scenarios such as emergency procedures or system failures to assess flight performance parameters that leverage the strengths of both simulators to provide a comprehensive and practical flight training experience. As technology advances, there is ample room for further research and innovation in VR and Desktop flight simulators. Future studies could explore hybrid approaches that harness the strengths of both simulator types, aiming to strike a balance between immersion, flight performance, and workload.

Additionally, efforts to lessen the workload in VR simulators and improve hardware requirements could lead to more comfortable and accessible training experiences. Furthermore, investigating the transferability of skills acquired in VR and Desktop simulators to real-world flight scenarios remains an essential avenue for future research. Long-term studies tracking the performance of pilots trained in each simulator type as they transition to actual aircraft could provide valuable insights into the effectiveness of simulator-based training.

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