Evaluation of Data Visualisation Technologies for Air Traffic Control

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Attestation of Authorship

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

Yemon Lee

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Abstract

Traditional data visualisation technologies in the context of air traffic control (ATC) currently utilise two-dimensional (2D) displays. However, presenting massive information on these traditional 2D displays may limit speed and efficiency of air traffic flow work. By comparison, virtual reality (VR) allows users to experience full immersion within a virtual environment. The virtual environment offers three-dimensional space compared to a two-dimensional image and computer screen. Therefore, VR technology has the potential to transform space and change flexibility in data visualisation.

This study investigates whether VR data visualisation technologies have the potential to positively transform the way humans interact with data in an immersive environment in the specific context of ATC. The core of this thesis is to compare VR data visualisation and more traditional 2D data visualisation, to determine whether immersive data visualisation enables human to have better control in information processing than non-immersive data visualisation.

This research incorporates a user study to examine the practicability of two similar user tasks between traditional 2D display and an immersive 3D environment using VR technology. Participants reported possible collisions between two prototypes with increasing levels of difficulties. Data was collected from participants' data logs and questionnaires. Statistical methods were used in data analysis and to summarise effective interpretations for the research hypothesis. The outcomes of this analysis are mixed, showing some potential advantages for VR technology in terms of improving human's performance in detecting a possible collision as well as analytical skill with increased speed and better accuracy. Such advantages are presumably that use of VR technologies can further strengthen problem solving capacity for air traffic controllers.

1. Introduction

The aim of this study is to investigate approaches for combining VR technologies with data visualisation and to discover their influence on the process of understanding data. This will be undertaken using a specific case study relating to air traffic control (ATC) data. Whilst there are relatively few in-flight collisions of aircraft as a result of well-established and successful work practices, there is an increasing concern over the growth of air traffic volume and the limitations of current ATC systems. There has been a 6-7% growth in air traffic per year particularly with passenger air transport as short and long journey flights have become increasingly affordable. More active flights across the wide airspace means higher workload and increased complexities for air traffic controllers (Corver & Aneziris, 2015; Lange, Hjalmarsson, Cooper, Ynnerman, & Duong, 2003; Shorrock & Kirwan, 2002).

Air traffic controllers have been using ATC system for more than 30 years (Lange, Hjalmarsson, Cooper, Ynnerman, & Duong, 2003). The computations of the ATC system are used to maintain separation distance between aircraft and to improve the routing of aircraft in airspace. ATC systems have become increasingly automated, however in certain circumstances they are still highly dependent on human operator judgement. The ATC traditional system also works as part of a bigger ATC collaborative system, with flight progress strip and air traffic controllers forming part of the collaborative system. The flight progress strip is used as an important co-ordinating medium that closely integrates with the radar and air traffic controllers. It provides the air traffic controllers with supporting information relating the state of aircraft activities (Fields, Wright, Marti, & Palmonari, 1998, p. 5). Replacing the traditional ATC system with new technologies would not be simple, as all parts of the ATC collaborative system are interlinked.

As the complexity and size of datasets increase, viewing and analysing complex visualisations using a standard computer and a mouse is not ideal (Ohno & Kageyama, 2007). Several alternative approaches have been identified in the past for ATC systems. One involved investigating the possible mix use of 3D stereoscopic visualisations, interaction features and human factors (Lange, Dang & Cooper, 2006). An innovative interface for ATC combined with 3D space and time was utilised in order to help the air traffic controller with a faster trajectory prediction system for future aircraft detection activities (Bagassi, Crescenzio & Persiani, 2010). 3D visualisation technique displayed the data on a semi-immersive VR theatre that aimed to provide air traffic controller a wider area to observe large numbers of aircraft (Lange, Hjalmarsson, Cooper, Ynnerman & Duong, 2003). Based on an initial review of the literature, there did not appear to be enough information in terms of exploring the utility of VR in ATC and it remains an open question as to whether VR has the potential to improve data visualisation in the ATC situation.

This research investigated and compared the difference of two methods of collision detection, the use of immersive 3D VR visualisation versus traditional 2D visualisation. VR technologies are able to provide a view control by head tracking function. The viewpoint in virtual world is adjusted with user's head position in the real world (Ohno & Kageyama, 2007).

This study in to the usage of VR technologies in ATC field provides some insight as to whether VR can enhance humans' ability in collision detection more effectively than the 2D visualisation.

1.1 Approach

This research was based on a combination of practice-based and scientific research methodologies. It involved three phases in the process of prototype iterations. Iterations cycles were based on feedback and identifying problems that require further development through testing with users.

Two final versions of radar visualisations were used in user tests. One utilised a traditional 2D screen and the other utilised a VR device. Further details of the user study are presented in Chapter 3, however as a general overview of the approach, participants were invited to use both versions and provide feedback on their experience.

The data analysis approach utilised in this study was inspired by the CAVE and Fishtank VR displays project of Demiralp, Jackson, Karelitz, Zhang, & Laidlaw (2006). Both qualitative and quantitative research were involved. Qualitative data was collected through observation and communication with participants. Some quantitative data was collected by using questionnaire that is designed for visualisation evaluation, however other quantitative data was collected by using data-logging techniques, and then analysed in statistical methods to compare which version of the two radar visualisations is more efficient. The qualitative data from the questionnaire revealed the participants' preference after testing both versions. Data from the questionnaire also provided better understanding of possible scenarios or problems in improving visualisation design.

1.2 Aims and Objectives

The objective of this research was to explore the potential for adapting new technologies that may enhance human working practices and to investigate the performance of VR technologies compared to traditional screen-based ATC visualisation technologies. It was hypothesised that the difference between using the 2D and VR application to detect a possible flight collision will show some valuable insight to support the potential development of future interfaces for both ATC and other similar applications.

Specifically, the research questions addressed in this thesis are:
When comparing a VR visualisation of air traffic with a 2D display-based application, which of the two

1) is more suitable for understanding aircraft trajectories

2) is more suitable for identifying potential aircraft collisions

The VR application was designed in such a way that functioned as a traditional 2D screen-based radar. The creation and the user evaluations of both applications provided statistics for VR user experiences related studies. The research outcomes will be described in detail in the conclusion chapter.

2. Literature Review

This chapter contextualises a variety of literature and previous research related to the current study. The aim of the literature review was to gain insights from different articles and projects; each with a different point of view about challenges and new techniques which provide a useful context to support and inform this research.

This research spans a number of different areas of inquiry as represented in the structure of the literature review. The air traffic control section introduces the background of air traffic control (ATC). ATC is a complex, safety-critical activity, with well-established and successful work practices. In order to further understand this context, this section includes an introduction of the history of ATC as well as the aspects of the operational background including the working practice of air traffic controller, paper flight strips, and the revolution of radar development. Although paper flight strips were not the focus of this work, they are mentioned due to their fundamental role in the work of air traffic controllers in the ATC system. Additionally, with the combination of technological innovations, the section also highlights some of the possibilities of combining VR technologies with data visualisation techniques in an immersive environment.

The second section on 2D and 3D data visualisation details the effectiveness of 2D and 3D user interfaces. It also describes the use of VR technologies in a few research studies which explains the advantages and disadvantages of both 2D and 3D displays.

The notions of 3D space and depth suggest the use of occlusion in virtual space and whether human can perceive depth and more information through the use of VR devices.

These notions of virtual space and immersion are further explored in the section on human interaction in virtual environments. This discusses the ease of adapting 3D visualisation in ATC particularly in the interaction between 3D and human activities, where human’s moving and viewing actions are the essential element in perceiving the virtual environment. A number of research studies explain the potentials enabled by using 3D data visualisation that can potentially allow human to discover more visual information in an immersive environment.

2.1 Air Traffic Control

ATC was first established in the early 1930s. By that time, there was a series of demands for an organised system of managing air traffic. Adoption of radar with approach and departure control facilities occurred in the 1950s to control and monitor the busy airspace surrounding airports. The radar includes a synchronized transmitter and a receiver that produces radio waves and transfers the radio waves for visual display.

In the late 1960s, computers were beginning to integrate radar with automation. Automation facilitated the connection of data from the flight plan with readings from the radar and produce alphanumeric screen of data that indicates the aircraft's position, speed and altitude. By 1975, all air traffic control centers and 61 airports were receiving real-time and in-flight data on computers (Nolan, 2010).

Yet many historical attempts to further automate the existing system failed because controllers remain attached to a key work artefact: the paper flight strip. Paper flight strip, radar, voice communication and visual observation are the primary tools for air traffic controller. A paper flight strip is a small strip of paper that is used to track a flight progress on a flight strip bay in ATC. The flight strip bay displays detailed information of different flights. In some countries, controllers are still required to use handwritten annotation on the paper strip to update the flight information before arranging them on a strip bay (Figure 1). The paper flight strips show the overlapping activities of the active flights in airspace (Doble & Hansman, 2004).

The main role of the air traffic controller in the broader ATC system is to monitor flights as they transit from long range to intermediate and close range flying in relation to an airport location. When monitoring these transitions, the air traffic controller typically checks on the radar first, and then paper flight strips (MacKay, 1999, p. 322).

Modern radar systems display the most updated information of aircraft's position, altitude, indicators of vertical altitudes, speed and flight movements predictions. Air traffic controllers use this information to understand distance between aircrafts, and to observe possible risk around the aircrafts (Ort, 2002). Additionally, the information enables the air traffic controller to communicate with the pilot to direct an aircraft along a route or to solve conflict in air traffic (MacKay, 1999, p. 322).

Figure 1. A strip bay at a high-altitude procedural area control sector in Indonesia (Fred775, 2004)

Traditional radar displays a two-dimensional visualisation of aircraft moving along pre-planned routes in the airspace, while paper strips allow air traffic controllers to track and modify flight information and flight plans (MacKay, 1999, p. 312). MacKay (1999) suggests incorporating new computer interface to replace the existing paper strips. The replacement of paper flight strips and improved radar visualisation are a couple of key directions in improving the ATC systems (Pfeiffer, Müller & Rosenthal, 2015). Today, most of the air traffic towers have replaced paper flight strips with electronic flight strips. Whilst some advances of electronic flight strips have been investigated, for example the use of augmented reality flight strips (Hurter, Lesbordes, Letondal, Vinot, & Conversy, 2012), these have not yet entered mainstream usage.

Flight information is derived from the Flight Data Processing System (FDPS), electronic flight strips arrange themselves automatically in a monitor integrated with FDPS system controlled view of flight information. A device with touchscreen function allows air traffic controller to input information. Historically, some air traffic controllers have not shifted from paper to electronic strips as they feel that the electronic strips technology would diminish their value as air traffic controllers (Masotti & Persiani, 2016, pp. 151-152), which perhaps is a consideration when integrating any new technology for ATC systems. However, whilst there have been new equipment and technological updates, new technologies cannot entirely replace the need for an air traffic controller. That human element is an important consideration in the current study.

Hopkin (1995) has discussed the design issues relating to flight progress strips and the systematic integration of flight information. Hopkin argued that it is difficult to integrate electronic strips logically with a plan view of air traffic space, especially when the air traffic is heavy. Tabular information display does not entirely resolve this problem either.

The existence of automation technologies has enabled computers to become better in recognising pattern and problem-solving. However, some scopes of automation tools have not met or exceeded human capabilities, such as detection of unexpected low-frequency events, complex four-dimensional trajectories assumptions and cognitive problem-solving (Wickens, Mavor & Parasuraman, 1998, p. 12).

According to Chang & Yeh (2010), air traffic controllers can be more effective at performing ATC tasks when changes and improvements are made in the system interface that consider how an air traffic controller interacts with the system. This has inspired the current research design, in which the development and implementation of ATC should also facilitate human strengths and should be driven by human-centered design approaches, as it is important to understand that appropriate use of tools can enhance human analytical skill and provide a better understanding of possible human failure. The process of interacting with and updating paper flight strips is a time-consuming activity for air traffic controller, it is likely that use of new technologies can enhance job performance for air traffic controllers by either replacing flights strips or removing the need to have them.

There have been some attempts to understand and define the requirements for future technologies supporting improved air traffic control systems (Durso & Manning, 2008; Swenson & Landis, 2006; Ky & Miallier, 2006), however to date there have been few reported attempts to formerly investigate different visualisation technologies deployed in the context of ATC systems. The available literature in this area predominately focuses on producing visualisation tools that can be used to understand the cognitive load on air traffic controllers (Karikawa, Aoyama, Takahashi, Furuta, Wakabayashi, & Kitamura, 2013) during simulation, understanding the tasks that air traffic controllers perform (Hirako, Sasaki, Yamazaki, Aoyama, Inoue, & Fukuda, 2013) or attempts to analyse air traffic controllers in practice as means to improve the selection and training of new air traffic controllers (Kang, Mandal, & Dyer, 2017).

The assertion that research into new visualisation technologies is sparse is supported by a recent review of visualisation technologies (Pfeiffer, Müller & Rosenthal, 2015) that only cites six articles published since 2010 with none focusing on truly immersive VR technologies. A more recent article is focused on identifying how information is extracted from traditional animated displays (Maggi, Fabrikant, Imbert & Hurter, 2016) which suggests that consideration of VR is an advancement of current knowledge and just being considered by researchers (Cordeil, Dwyer & Hurter, 2016), though the concept of the remote tower is clearly in the formative stage and not supported by a user evaluation. The research in this thesis is therefore a timely addition to the current body of knowledge related to understanding how VR can impact information processing in ATC systems.

2.2 2D and 3D Data Visualisation

Data visualisation refers to the communication of information using graphical representations. As a mechanism for communication, well-presented visualisations are also applied to problem solving and data analysis, it processes information quickly and comprehend huge amounts of data (Ward, Grinstein, & Keim, 2015, p. 1-2).

The main difference between 2D and 3D data visualisation is that 3D suggests a range of depth cues and perspective in user interface (Ware, 2004). Cockburn & McKenzie (2004) provides a summary of major elements that are including in depth cues as follows.

- Linear perspective - Position of objects appear to converge on a vanishing point on the horizon.

- Shading/ Cast shadows - Shadows are used for supporting interpretation and altitude. It suggests depth when one object casts a shadow on another within a light source.

- Occlusion - An object appears closer to the viewer when it overlaps another.

- Texture gradient - Gradual change in appearance of objects which relates to relative size and detail of textured surface changes from coarse to fine depending on distance.

St. John et al (2001) argued that a 3D view is not important, as the availability of information and well-designed 2D displays that use graphical encoding are capable of obtaining the same benefits. Their research argued that 2D views are better for understanding relative positions of two objects and locations. This assertion was tested with 32 participants in four experiments. The experiments revealed that viewing 3D visualisation on a 2D screen with mouse controller helped them in understanding simple shapes. It gave extra depth cues than 2D views, and participants' reaction times were two to three times faster than in 2D views. However, in 2D views, participants performed better in pointing out relative positions of two objects than in 3D views.

Savery et al. (2013) showed the advantage of using tangible and multi-touch user interfaces to avoid indirect visual feedback from screens. Through a user study with air traffic controllers they found that users adapted the two-handed interactions and different modalities quickly.

Following on from the above studies, this research will examine how VR performs versus 2D when it comes to pointing out relative positions of objects. Furthermore, a VR device does not necessarily require a mouse controller in navigation, which could potentially increase participants' reaction time.

A number of studies were conducted after St. John's, which included 3D stereoscopic visualisations for ATC (Lange, Dang & Cooper, 2006), prediction lines for future aircraft trajectories (Bagassi, Crescenzio & Persiani, 2010), visualisation for conflict resolution (Lange, Dang & Cooper, 2006) and 3D visualisation of real time data (Lange, Hjalmarsson, Cooper, Ynnerman & Duong, 2003). Whilst these studies and their approaches were centred around methods designed to assist air traffic controllers' work, they were predominantly based on utilising flat screens to present the data to the air traffic controller. Lange, Dang & Cooper (2006) is the one exception, as this work focused mostly on the interactions between 3D and VR, and they investigated the potential of how the interactions can help human to receive more information.

This research concerns the data visualisation display in different environments and how human perceive information different from a 2D flat screen and an immersive virtual reality experience. To the best of the authors' knowledge, there is still space to explore the application of Virtual Reality (VR) in ATC and it remains an open question as to whether VR has the potential to improve data visualisation in the ATC situation.

2.3 The Notions of 3D Space and Depth

The human vision system allows human to estimate distance and to receive three-dimensional information from the world, however, the human vision system does not perform the same at closer range as for further distances (Dhome, Richetin, Lapreste, & Rives, 1989, pp. 1265–1266).

Scherffig (2016) stated that the nature of spatial presence in virtual reality is directly reflected from human bodily activities, in which the presence occurred when human appears to have the sense of "being there" and have the ability to perform activities in the environment. Scherffig also remarked that a virtual environment is enacted from cyberspace, where players experience interaction with games and other media through machine feedback, where action perception plays in three-dimensional spaces. The use of computer-based feedback control systems enables a shift in this paradigm and allow human to determine their presence and sensations through actions. The development of this perceptual technologies creates extra sensations that is coupled with human experience.

Such research suggested that the creation of 3D space has been widely examined in the past and humans can possibly shift their perception of spatial presence in between virtual reality and reality. In this case, it may also apply in working environments, and in the case of this research is suggested that air traffic controller may be able to shift their working environment from 2D display to head-mounted display and perform their working skills in the virtual space as effectively as in reality.

According to Cutting & Vishton (1995), occlusion happens when one object is blocking or hidden from another object in space, it brings additional information about depth to human vision. Cutting & Vishton also stated that lights and shadows have also been the main source of information about depth. When luminance gradually increases, the object appears to move forward, which brings assumptions of distance between objects and space. Brightness, lights, and shadows also provide information about object shapes and they can be considered as the phenomenon of transparency. Cutting & Vishton have undertaken further investigation on shapes and distances by analysing the difference of same-shaped and different-shaped across distances.

The concept of occlusion in space is also important in visualisation as discussed by Cockburn & McKenzie (2004) in section 2.3. It can also be examined in virtual space as to investigate whether human can perceive depth and more information through the use of a VR device. Second, distance between objects can be a potential function to add into existing ATC radar visualisation in order to allow controller to perceive additional flight information.

2.4 Human Interaction in Virtual Environment

According to Donalek et al. (2014), humans have a good pattern recognition and the ability to discover new knowledge through visual exploration. This remarkable skill can be the key methodological challenge for data science in the 21st century. Donalek et al. suggested that new data visualisation tools are required to reveal hidden patterns in massive datasets. VR has the potential to become a new data visualising tool, where the virtual environment allows users to interact with data in three-dimensional space. Examples of such immersive interaction with data are becoming more commonplace in the research literature (Marks, Estevez & Connor, 2014). Donalek et al. (2014) has also suggested that this pattern recognition skill can be a new methodological challenge for data science in the future. According to Ware (2004), the perception of pattern recognition is fundamental in data visualisation. Improvements and refinements can be made to minimise visual interference by adjusting colours, texture, motions and stereoscopic depth channels. Such suggestions of visual adjustments can be useful in the process of VR data visualisation development when a number of 3D aircraft models may require separation depending on the design requirements.

Similarly, Ohno and Kageyama (2007) examined VR technologies that can make the data become more visible by incorporating volume rendering and 3D semi-transparency in virtual space. Ohno and Kageyama also found that volume rendering can reduce the burden of data analysis effectively through testing with users. Katosvich (2016) mentioned that navigating in virtual space allows users to bypass the traditional gestures of clicking, scrolling and swiping the interface.

Hence, Katosvich suggested researchers experiment with storytelling methods in virtual space.

In "Is the Nasdaq in Another Bubble?" project, Katosvich observed how users interacted with storytelling visualisation, where users navigated around the visualisation in 360 degrees. This project is the first VR tour that visualised stock market data and it was nominated as “Data Visualisation of the Year” in 2015. It showed a new experience in digital storytelling, where users enjoyed interacting with its contents. Users could experience a sense of fear and uncertainty through three-dimensional data visualisation and they could navigate the Nasdaq Stock exchange data through 21 years of growth and falls.

Billen et al. (2008) gave examples of users being able to change views and directly grab and rotate objects in a virtual space, performing humans’ natural gesture and movements. And more importantly, humans perceive three-dimensional worlds naturally, therefore VR technologies can potentially allow human brains to interpret more visual information. Billen et al. added that it is also essential to maintain high frame rate rendering in the interactive virtual environments to maintain a realistic immersive experience when viewing larger data sets. Therefore, interactivity functions in virtual environments can allow users to speed up data analysis as well as to discover new behaviours and knowledge.

The benefits of VR such as 3D perception enabled by head tracking functionality and the ease of allowing users to select positions and interact in 3D space, tend to suggest that immersive data visualisation has the potential to improve complex data visualisation tasks, such as ATC. According to Chang & Yeh (2010), human error resulted in mismatched interfaces between air traffic controllers and the ATC system components. Therefore, proper adjustments of technological innovations and explorations of the interactions between human performance and new technology system may have positive influences on each other.

2.5 Summary

Analysis of the literature has shown that the ATC systems are slow to adapt to technological change. In part, this is driven by the safety critical nature of the environment in which they are used, but there is also potential that air traffic controllers are concerned over the perception of the importance of their roles. There is a sparseness of research studies that investigate the potential for new technologies, and recent research has suggested that new display interfaces and the removal of the paper flight strip are areas that should be considered.

The literature has also shown that a combination of virtual reality and 3D visualisation has the potential to radically transform how humans interpret data. Despite this, there have been few recent attempts to explore the use of virtual reality technologies in the context of ATC. Whilst a number of studies were conducted in the 1980s and 1990s, these studies would have been limited by the available technology of the time. More recent studies are just starting to be reported (Cordeil, Dwyer & Hurter, 2016), but have clearly not yet progressed to formal user evaluation. The emergence of low cost, consumer VR technologies has created an explosion of interest in VR which has not yet been adopted by ATC system researchers, despite some interest in using both VR and AR systems in the design of future systems (Rottermanner et al., 2017).

The research described in this thesis therefore is both timely and relevant in terms of understanding the potential for adopting VR based interfaces in ATC and makes a useful contribution through reporting the outcomes of a formal user evaluation of VR technologies in comparison to more traditional displays.

3. Methodology

The chapter discusses the process and approaches taken for evaluating VR based visualisation of ATC data in comparison to more traditional 2D displays. This research adopted a practice-based method in the early design process. To gain advanced knowledge in this study; observation, design iterations, and reflective journaling form a knowledge creation cycle during the design and implementation process. This is described in more detail in section 3.1, however the outcome of this was a number of prototypes ready for further analysis in a user test.

The objective of the user test was therefore to collect data from the user experience of two different applications. Data collection methods were inspired by the CAVE and Fishtank VR displays project of Demiralp, Jackson, Karelitz, Zhang, & Laidlaw (2006), which suggested how to adapt qualitative and quantitative study when comparing different tools.

The user tasks section discusses the application plan in detail, which includes flight path and scenario planning. The user test setup describes the space allocation plan for both application settings and required equipment for the user test.

For data collection, data-logging techniques are used to capture users' data during user tests. These techniques and rationale for tracking users' data make the verification process became less complex. Collected data and statistical results will be discussed in the results chapter.

3.1 Practice-based Research Process

In a creative technology environment, high responsiveness sparks creativity, where new insights emerge throughout an iterative process and inform the ongoing development process (Edmonds et al., 2005, p.4-5). The research process includes ongoing reflections in practice and finding a new way that considers the correlation between knowing and doing as to enhance the quality and meaning of the final application.

In this research, both final applications used in the user evaluation are emphasised and generated from the same creative process, which reflects a new understanding of practice and data analysis. A practiced-based research process focuses on self-observations, analysis, ongoing reflections, peer reviews and design iterations. The purpose of a practice-based research method is to gain new insights and understandings through peer reviews and observations during the creative cycle.

To help explain the theory of practice-based research method, Figure 2 provides a visual outline of the knowledge creation cycle based on practice-based research method, which is used as a guideline in this study. In the diagram, experiments, new knowledge integration and implementation are the focus points in the design and implementation chapter, where new knowledges are formed from the process of design iterations of both prototypes after receiving feedbacks from peers' review and through the process of self-reflection.

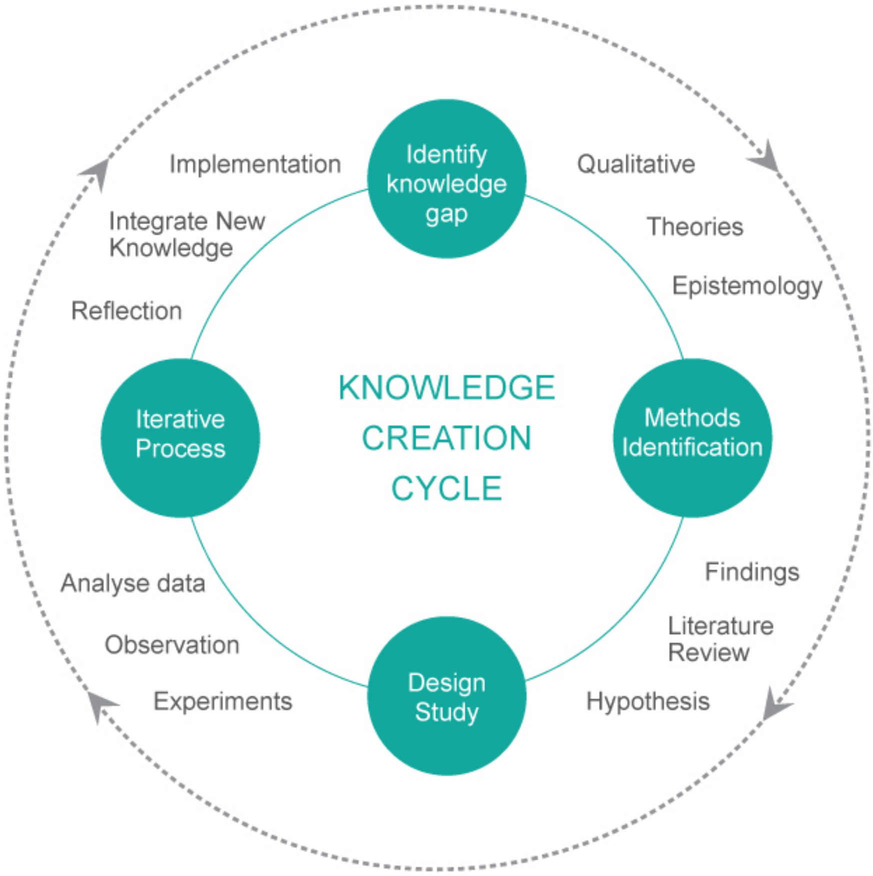

Figure 2. Practice-based knowledge creation cycle. Inspired and modified from *Diagram of practice-based research involving clinicians in research steps*, by Mold, J. W., 2005.

In the context of this research, a practice-based method was adopted during a prototyping phase. The purpose of this phase was to rapidly iterate through potential visualisation representations to propose suitable candidate representations for inclusion in the formal user evaluation, which was essentially a second phase of the research. The outcomes of the first phase of research are reported in Chapter 4.

3.2 CAVE and Fishtank VR

The design and research methodologies for the second phase of this study are inspired by the CAVE and Fishtank VR display system project. The purpose of the CAVE and Fishtank VR project is to compare two different display environments by measuring user performance and error rate values with a visual search task. For data analysis, task completion time for both display types were compared by box plot graphs and bar graphs. The result of this study showed that users performed significantly better in Fishtank VR than in the CAVE because of better screen resolution, brightness, quality of imagery and the ease of use. The researchers suggested that VR display is more effective in terms of accuracy and participants performed faster to complete the task (Demiralp, Jackson, Karelitz, Zhang, & Laidlaw, 2006, p. 326). This study example provides useful techniques for conducting quantitative and qualitative study particularly related to user test and data collection for this research. Also, the works of this literature exemplify that having data visualisation in virtual space can be a new aspect to look at.

3.3 User Tasks

Each user was asked to observe air traffic using two different methods of visualisation. Each visualisation lasted approximately 7 minutes. The task was to identify possible flight collisions in both visualisations. A game controller was given to the user. The user was asked to press the controller button when he/she felt that a potential flight collision would occur. At the time the controller button was pressed, the user would identify which aircraft were involved and call them out. This information would be recorded by the author. Incorrect decisions, true or false answers, and data logging from the game controller with detection times were all recorded for later analysis.

The users were encouraged to make comments and share their opinions during the user tests. Their opinions were summarised in the qualitative data section (section 5.2). They were then asked to complete a questionnaire (Appendix 7) that included questions related to their user experiences, such as how well the two applications worked in doing ATC related work and their overall preference.

Each visualisation contained six scenarios. Collisions were planned in four of the scenarios and no collision in the other two. In the first scenario, the time duration was the shortest and number of aircraft was the lowest. Both, duration and number of aircraft were increased in the subsequent scenarios. Scenario 6 took as long as 120 seconds, markedly longer than 40 seconds in scenario 1. The level of complexity went up from two aircraft in early scenarios to seven aircraft in later scenarios.

To achieve a fair comparison of the two applications, certain aspects of the flight path designs were set to be identical in the 2D (Figure 3) and VR (Figure 4) applications. These aspects included duration, speed, number of collision and number of aircraft in each scenario. However, the flight paths themselves were different which removes the potential for users to simply learn or recognise the patterns from their first set of tasks.

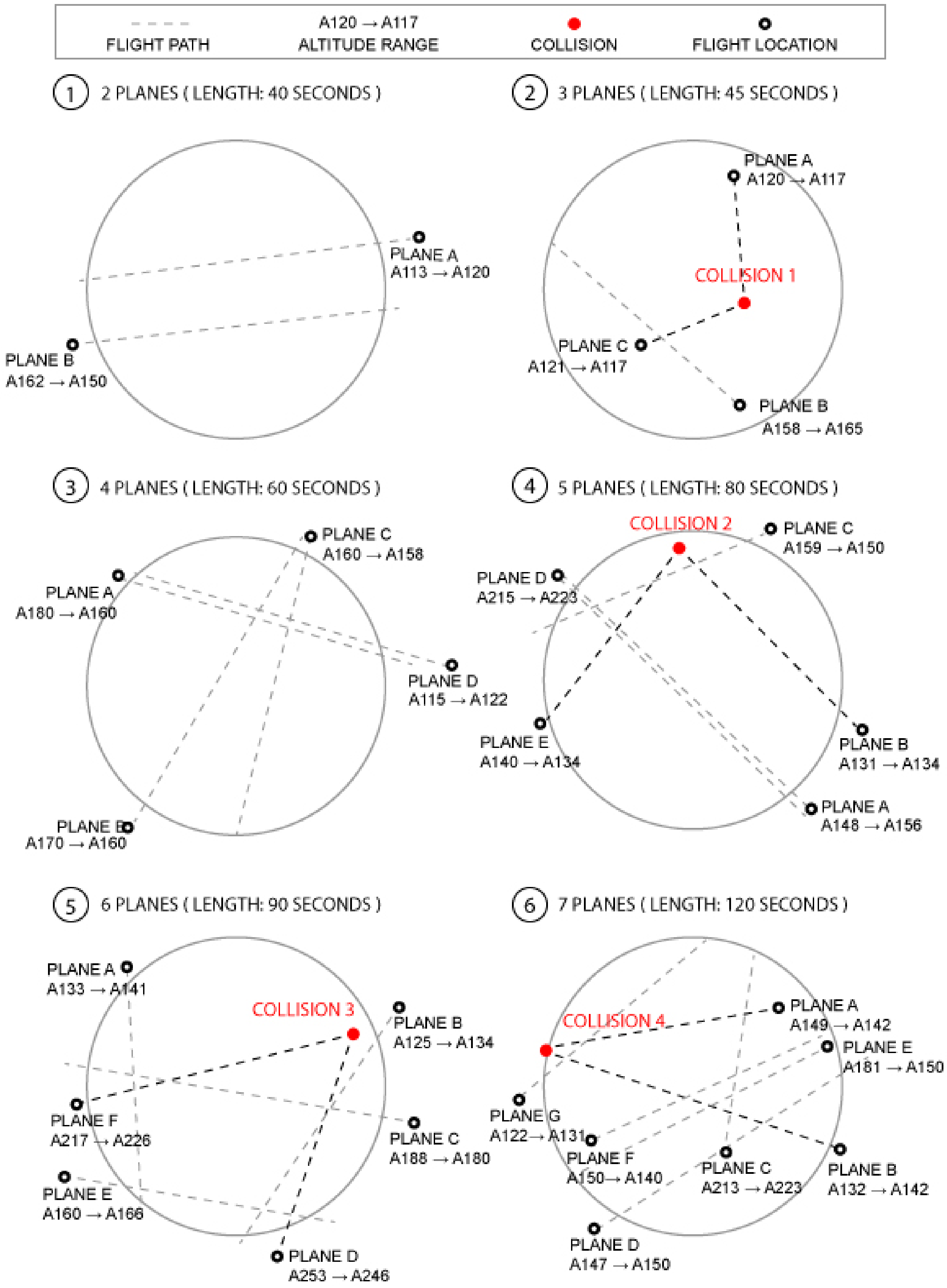

Figure 3. Flight path plan for 2D application

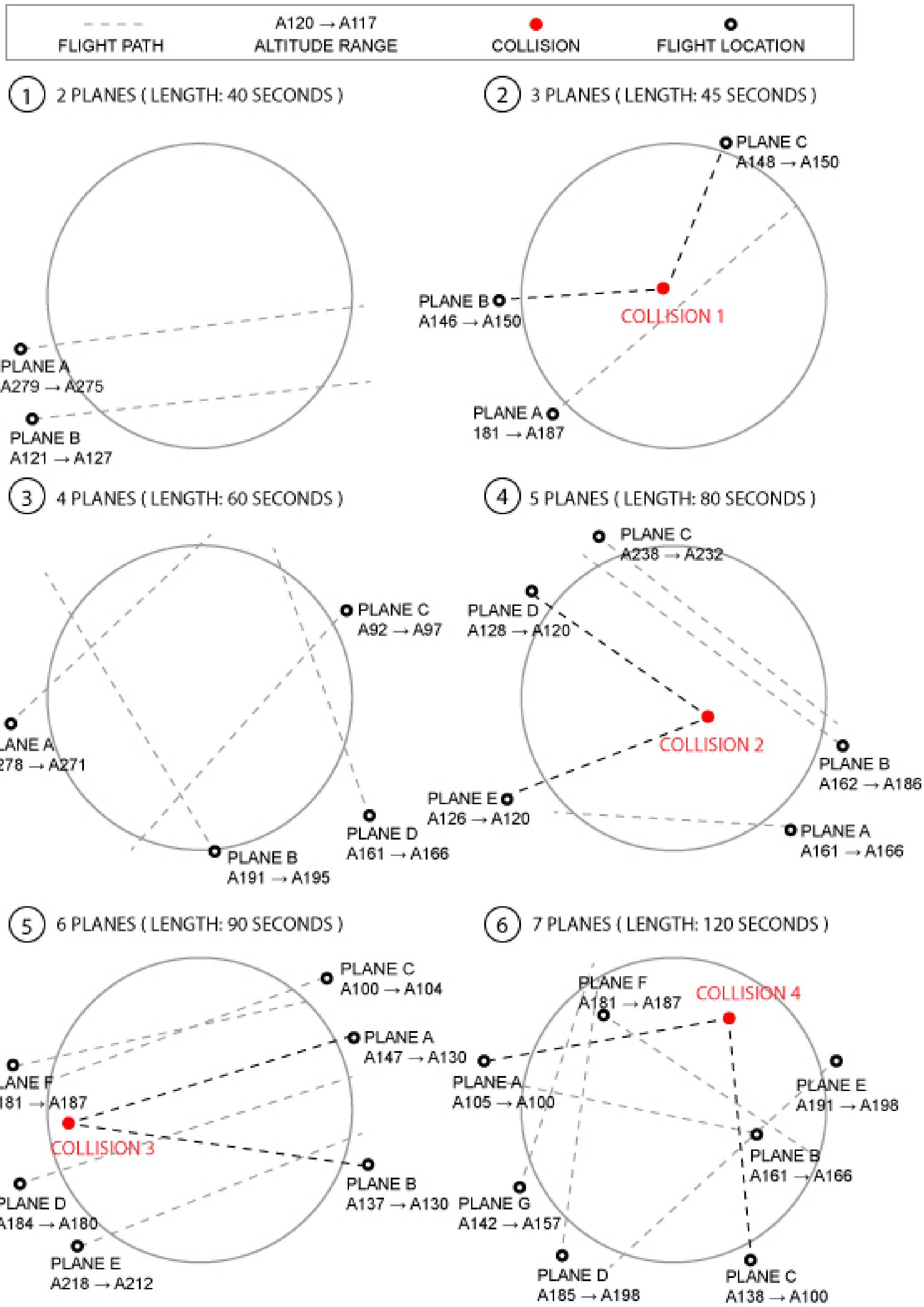

Figure 4. Flight path plan for VR application

3.4 User Test Setup

Using a laptop and a projector, a 1.5m x 1.5m image of 2D visualisation was projected on a white wall (Figure 5). The size of the projected image was similar to the one experienced in VR, which was also 1.5m x 1.5m.

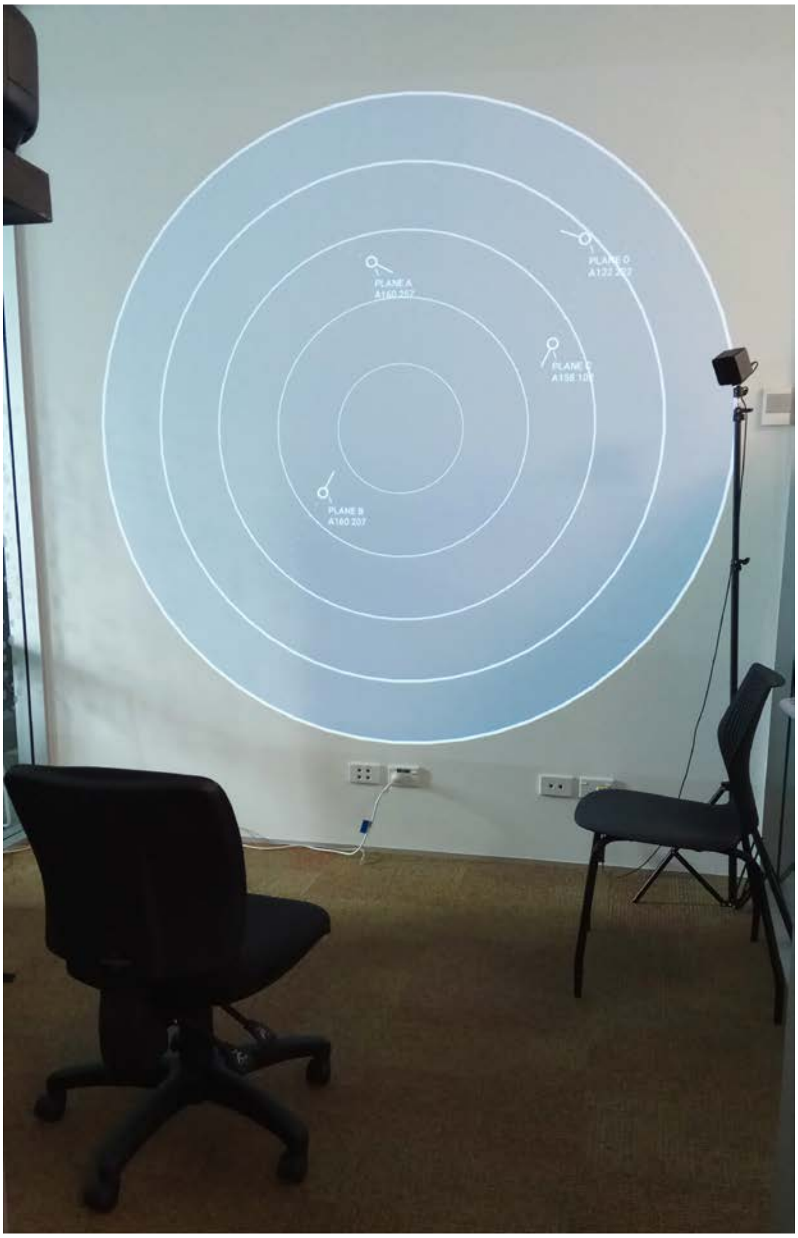

Figure 5. Projection setup for user test

To maintain the same distance as the VR scenario, where the camera was 1m away from the radar, the users were asked to sit in the middle of the room during user test (Figure 6), which was approximately 1m away from the projected image.

Figure 6. User tested on 2D application

The VR visualisation was conducted with the users sitting in the middle of the room. The purpose of having users sitting in the middle of the room for both 2D and VR visualisations was to make sure the users see the visualisations from similar distance and scale. In Figure 7, the image projected on the wall was a replicated same scale image of what this particular user saw using his VR device, and it was for the benefit of the researcher.

Figure 7. User tested on VR application

3.5 Data Collection

Computer-based data-logging techniques have been adopted in this research. Data-logging offers certain advantages for the experimental settings, it records real-time data in an informative way and improves the quality of measurement by using electronic devices (Rogers & Wild, 1996, p. 131). These techniques could enhance the accuracy of the results and facilitate the interpretation of collected data.

The data-logging method includes the use of a game controller. User test responses are registered by pressing on game controller button. These responses will be recorded and saved into computer for further data analysis. Raw data in Appendix 1 are collected and saved in CSV format, each data entry represents the time when participant pressed the button on the game controller. Collected data will be displayed and compared in graphs and tables in the result chapter.

User experience related information will be collected using questionnaire given in Appendix 7. Users' answers will also be compared and analysed with users' performance in the result chapter.

4. Design and Implementation

To evaluate the hypothesis, two different applications were selected from the design experiments. This chapter covers the process of design iterations of both 2D display and VR applications, which focuses on mostly visual, experiments, and peers' feedback. Both visualisations were created using the Unity3D game engine, as Unity3D allows users to develop both 2D and 3D visualisations in one working environment. Also, Unity3D is a cross platform game engine, which it is easy to deploy for PC, mobile app and VR devices.

In the 2D data visualisation on screen section, the development process has shifted from experimenting with image projections to a reproduction approach, which aimed to obtain the most important features of the current commercial radar after an ATC tower visit.

In the VR data visualisation section, the design iterations focus on the user feedback from a number of prototype testing. The experimental procedure includes testing with different camera position settings in multiple representations, ergonomics consideration and VR technical solutions.

Figure 8 is the timeline of design iterations for both applications, which contains the major changes from early development to later iterations.

2D Application		VR Application	
Prototype 1	* Use of radar map projection * Degree readings * Use of aircraft 3D models	Prototype 1	* Camera is positioned in the middle * Google VR plugin * Use of aircraft 3D models * History trail is visualised in white colour * Head-mounted Device
		Prototype 2	* Camera is positioned in the middle * Realistic approach * Experiment with skybox variations * Use VR pointer to see flight information * History trail is visualised in white and red colours
Prototype 2	* Orthographic projection * Change of colour * Simplified objects * Changed of scale * History trail is visualised with white dots	Prototype 3	* Camera is positioned 15 units upwards * Radar is positioned 50 units away from camera * Flight information is attached to aircraft model
		Prototype 4	* Change to frontal view * Experiment with simplified objects * Enhance shading and depth * Flight information is always facing the camera * History trail is visualised with white dots * HTC Vive

Figure 8. Design iteration timeline

4.1 2D Data visualisation on screen

The first phase of this research involves the creation of an abstraction of the radar display utilised by air traffic controllers. This application is the baseline against which potential immersive visualisations will be compared in the results chapter.

In the early experimental process, use of different image maps and aircraft models were the main focus. Prototype 1 (Figure 9) was created using the Unity3D game engine. Radar map was projected onto a plane model, forming the radar plane. A few aircraft models were then added, to simulate departing and arriving flights.

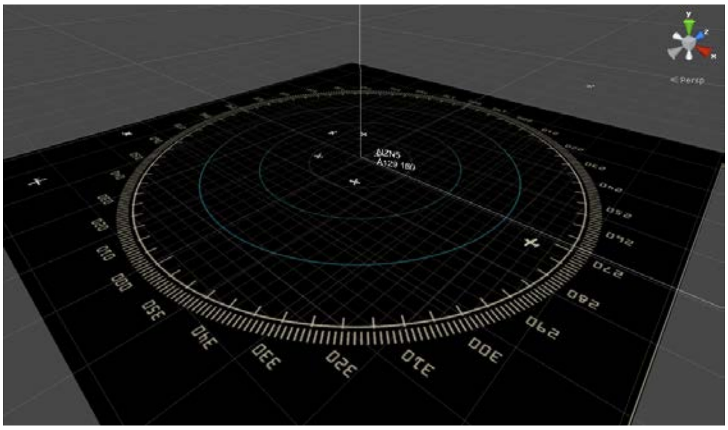

Figure 9. Screenshot of 2D prototype 1

In the initial iteration, the details of map projection were rather blurry when viewed from the top (Figure 10). The scale of planes and radar required adjustments as they appeared slightly out of proportion.

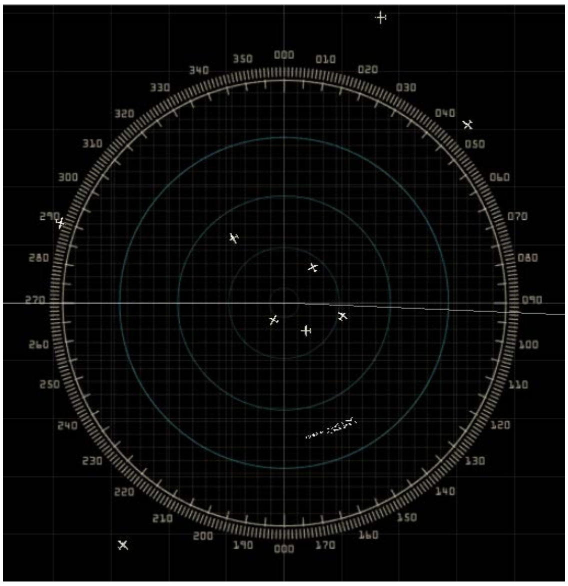

Figure 10. 2D prototype 1 from top view

4.1.1 Air Traffic Control Tower

Both 2D and VR visualisations are presented based on a commercial radar in terms of graphics, information, and functions. This presentation was informed by a visit to an air traffic control tower. An experienced air traffic controller gave a helpful introduction during the site visit session. The air traffic controller introduced an existing commercial radar (Figure 11) at the ATC tower. The coverage area of this commercial radar has a maximum range of 250 miles and flight information are displayed on a 26.4 x 25.9-inch LCD display. The air traffic controller also showed us how to operate the radar system. For example, an air traffic controller used a computer mouse to view certain flight related information by hovering the pointer over certain symbols on the radar screen. Using the same system, he also inputted flight number by keyboard to obtain detailed flight information.

Figure 11. Airways site visit in Auckland

The air traffic controller also went through the meanings of the readings and symbols (Figure 12) of a commercial radar screen as follows:

1) Predictor line
2) Flight location
3) Target history trail
4) Altitude
5) Flight Number
6) Speed
7) Destination

This information is helpful when preparing user instruction sheet for the user test. To simplify the complexity of a commercial radar, both 2D and VR visualisations will only focus on the first six basic readings and symbols. Appendix 2 details the information and instructions for participants to use before they begin the user test.

Figure 12. Detail from commercial radar

4.1.2 2D Design Iterations

In later design iterations, the objective of the 2D visualisation is to replicate a commercial radar. The radar map projection was removed as the information around the dial was hard to view and this information was not necessary for the user test. The overall graphics presentation of the second prototype (Figure 13) was created based on commercial radar from ATC tower. It contains the main features of a commercial radar such as colour, predictor line, history trail, and data-tag. The predictor line and the history trail indicate the flight's current orientation and position over time, whereas the data-tag provides flight number, altitude, and speed information (Nunes & Scholl, 2005, p. 182).

The ratio of the distance of camera and the distance of aircraft required different settings to test during development. After a few experiments with relative distances of camera and aircraft in Unity3D, the size of the radar plane was then set to 100 x 100 units in Unity3D and the camera was set to 50 units away from the radar. The final 2D radar visualisation can be viewed online (https://youtu.be/-8iU0xYjtEQ).

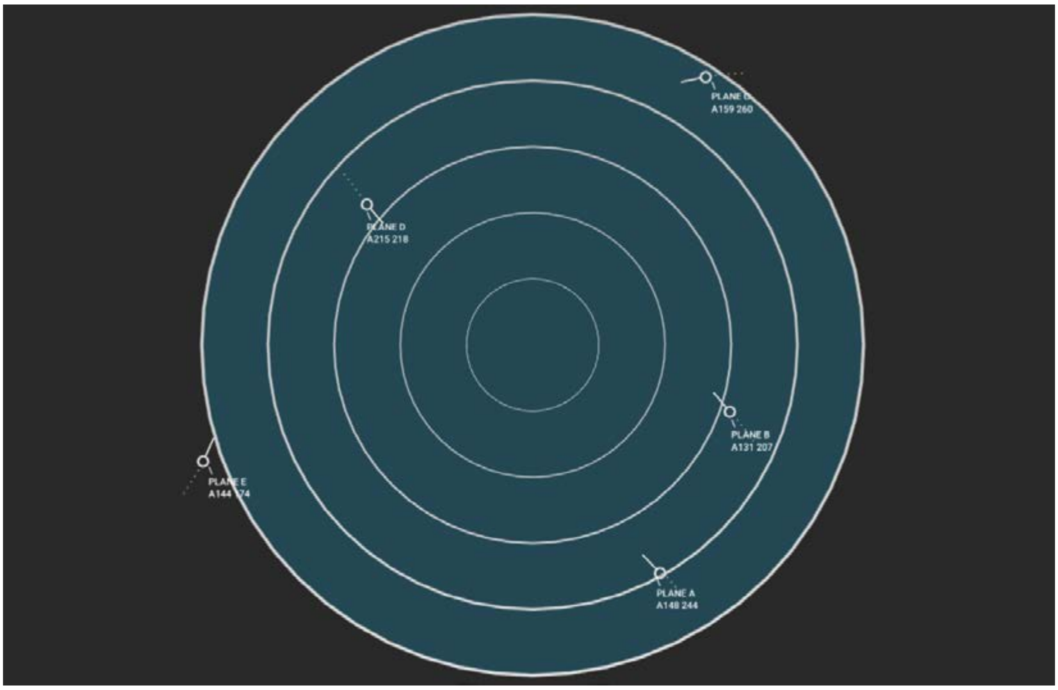

Figure 13. Screenshot of 2D prototype 2

4.2 VR data visualisation

This phase utilises a practice-based methodology to explore different data representations of air traffic control (ATC) data. The process of this phase aims to explore multiple representations and select one for the user test.

The idea of the VR application is to allow users to experience a radar visualisation in an immersive environment. Prototype 1 was developed based on the working file of 2D application in Unity3D with Google VR plugin (Figure 14). The camera was positioned in the middle of the scene. The camera was positioned in a way that positioned users standing in the middle of the radar (ATC tower viewpoint) in the virtual environment, viewing air traffic flights and navigating the scene in 360 degrees environment. In addition, first-person controller camera setting, a graphical perspective from the viewpoint of the user, allowed the user to determine heights and distances of the aircraft as if they were viewing it from an ATC tower.

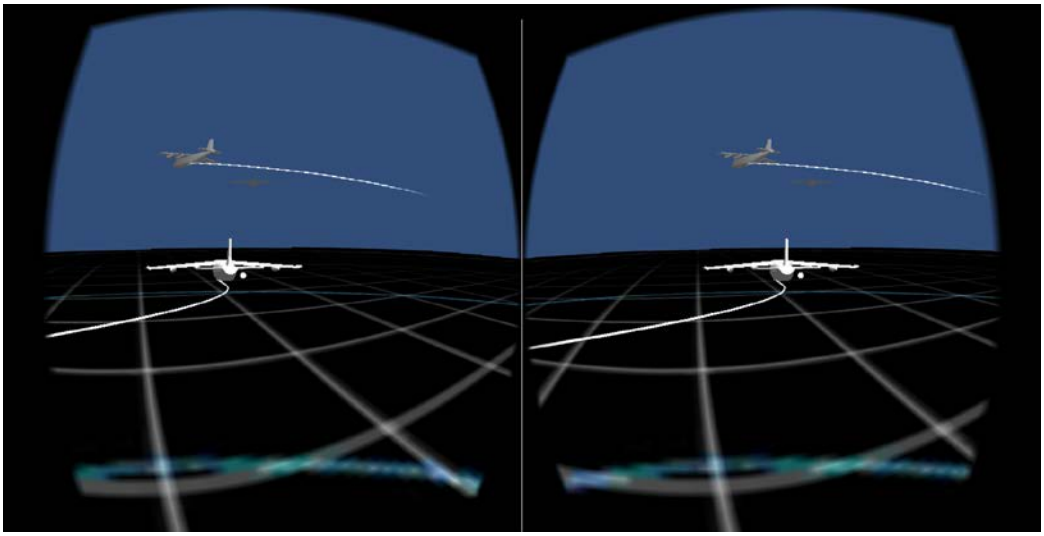

Figure 14. Screenshot of VR prototype 1

4.2.1 VR Design Iterations

In prototype 2, skybox function was added into the scene (Figure 15) to achieve a more realistic visualisation. Skybox function is a panoramic effect to replicate the sky. The outcome was not ideal unfortunately. The addition of the skybox function made viewing harder. The skybox graphics were distracting, and parts of the scenes were too dark. Further, the objects were too far from camera view and the additional graphics and effects from skybox function made it much harder to measure heights and distances. Second, the 3D model of the plane contained too many polygons which inevitably slowed down rendering.

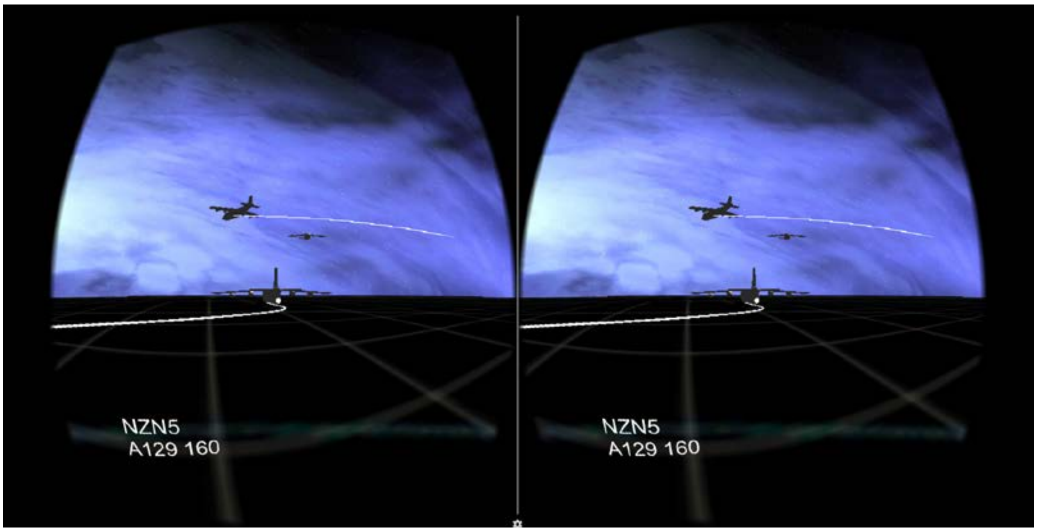

Figure 15. Screenshot of VR prototype 2

Different types of skybox variations were tested (Figure 16). The discussion from peers meeting suggested that viewing from the middle of radar was not practical. Viewing from the middle of radar required the users to turn their head around at times, which could be harmful for users' necks. Another downside was when viewing from the middle of the radar, the users would only be able to see what is in front of them, not what's behind them.

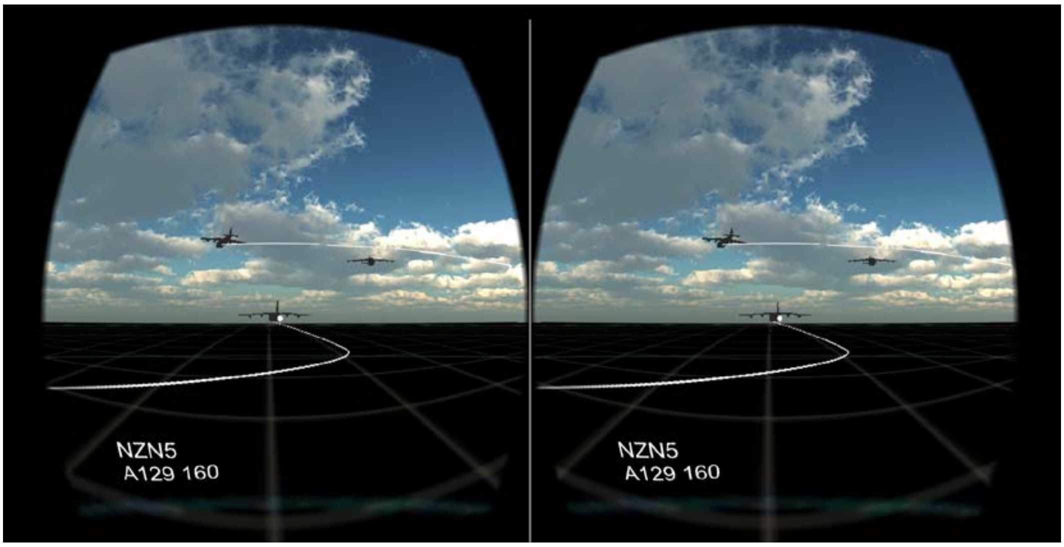

Figure 16. Skybox variation in VR prototype 2

A VR pointer was added during the early development. VR pointer is part of Google VR component. The pointer works like a cursor. The pointer could be used to highlight a particular aircraft, which would result in related flight information being displayed at the bottom left of the VR display (Figure 17). From the peers' feedback, the VR pointer proved to be unsuitable. The VR pointer could only highlight one aircraft at a time and as the aircraft moved, the pointer needed to be moved along at the same time. It was difficult to control, displayed limited information and therefore not practical.

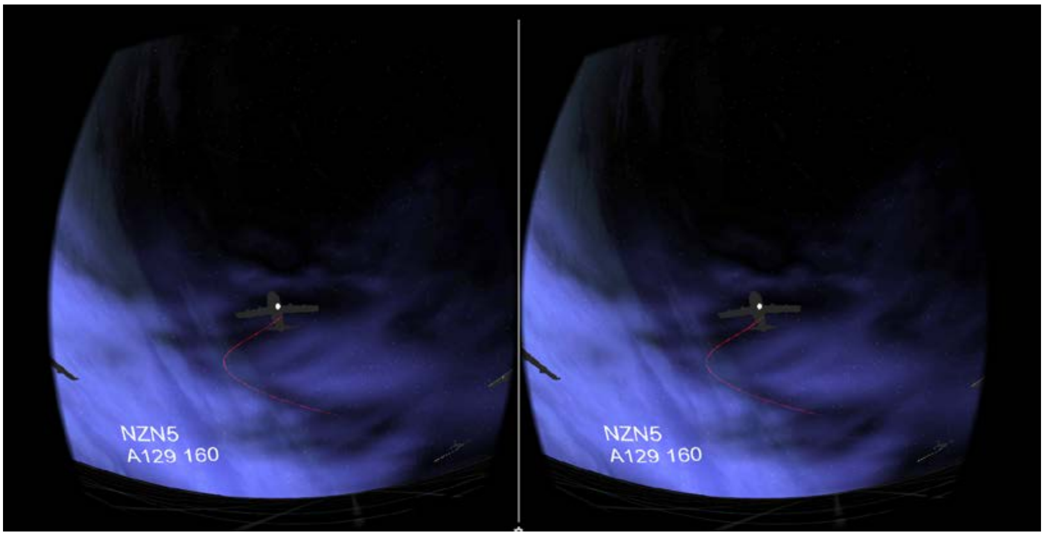

Figure 17. Detail from VR prototype 2

To address the ergonomic issues in prototype 2, in prototype 3 (Figure 18), the camera was moved 15 units upwards in Y axis at Unity3D, and also the radar plane was 50 units away from the camera. Further, the flight information was made visible and displayed next to each aircraft. These settings allowed users to view the visualisation with minimum neck movements. Unfortunately, the adjustments meant the distances users were viewing things from were too far. The objects were too small to be viewed clearly.

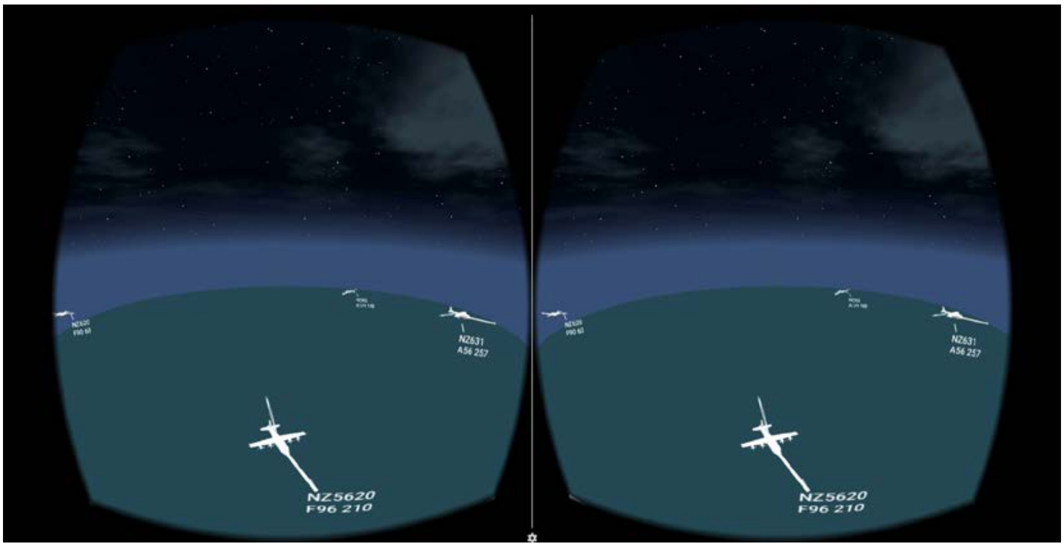

Figure 18. Screenshot of VR prototype 3

Prototype 4 was an experiment with viewing the radar at a frontal view (Figure 19), where the radar plane and aircraft were rotated to face the camera. The rationale of this setting was to match the setting of 2D version including the use of colours, symbols, viewing angle, and simplicity. In addition, this setting solved both the ergonomic issues in prototype 2 and the problem of viewing distance in prototype 3.

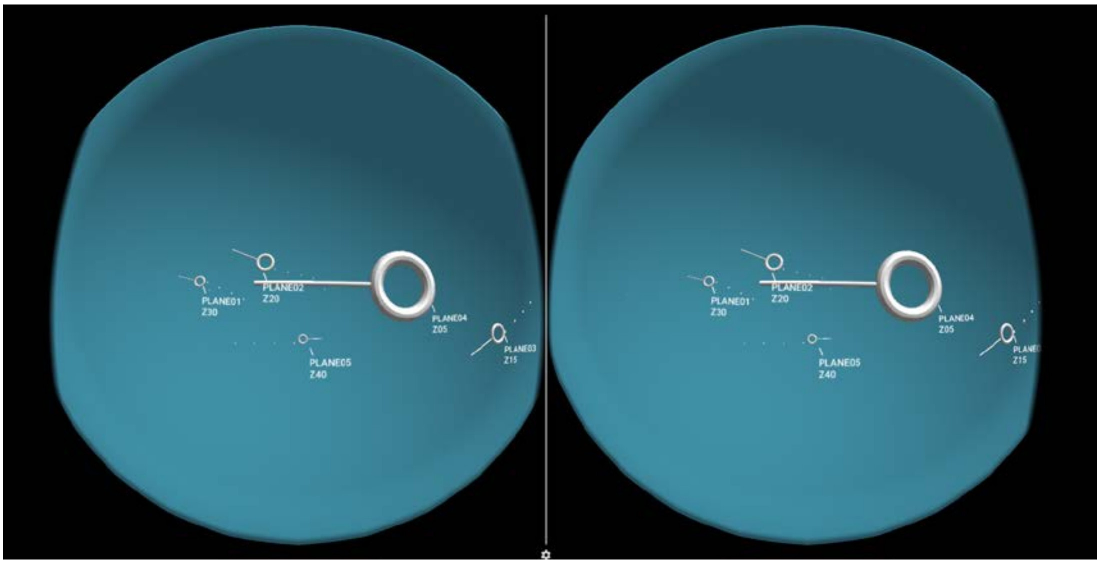

Figure 19. Screenshot of VR prototype 4

Further, to address the earlier mentioned rendering issue in prototype 2, the aircraft model was replaced with simplified objects. Different approaches of simplified 3D symbols were experimented in this development (Figure 20 & 21), as each variation gave a different sense of depth and shadows.

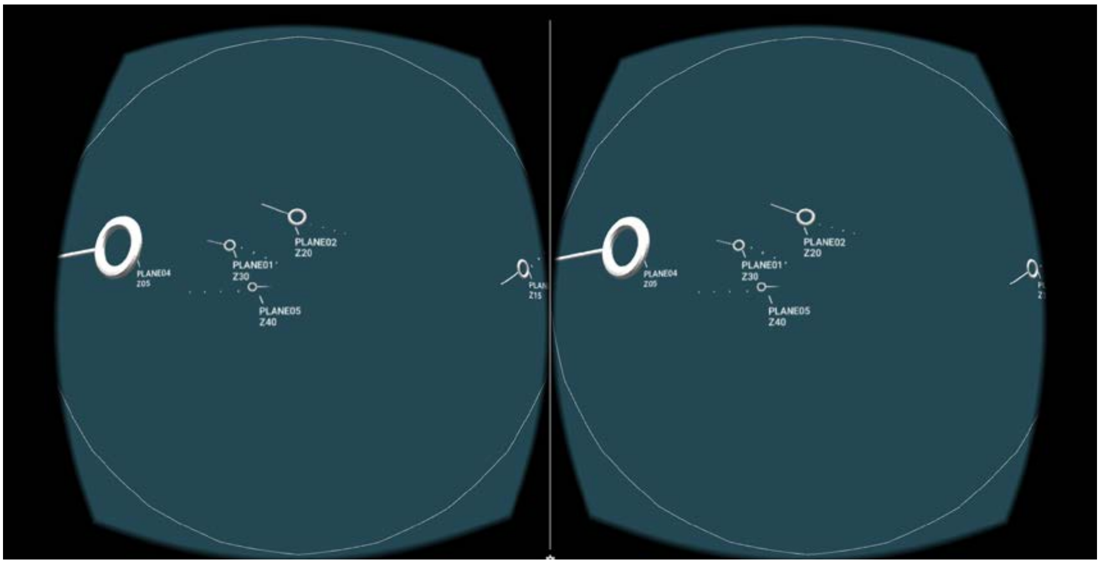

Figure 20. Symbol variation 1 in VR prototype 4

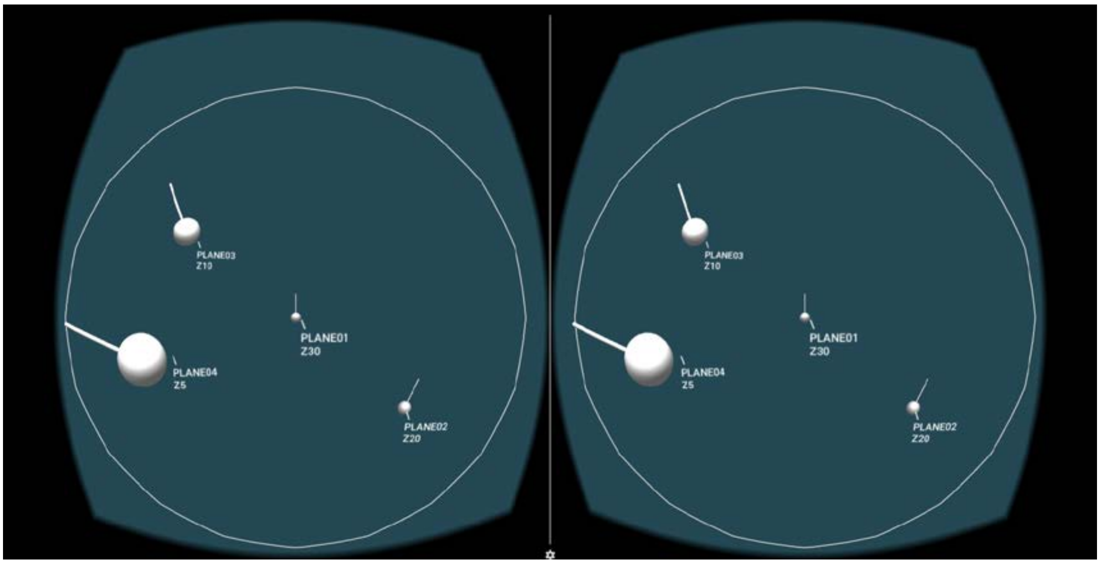

Figure 21. Symbol variation 2 in VR prototype 4

Further adjustments were applied in prototype 4, looking at how to enhance the shading and depths, allowing users to perceive the difference of scales between the aircraft in the scene. First, the flight information was adjusted. Following the adjustment, the information was set so that it would always face the camera without any distortion to shape and font size (Figure 22).

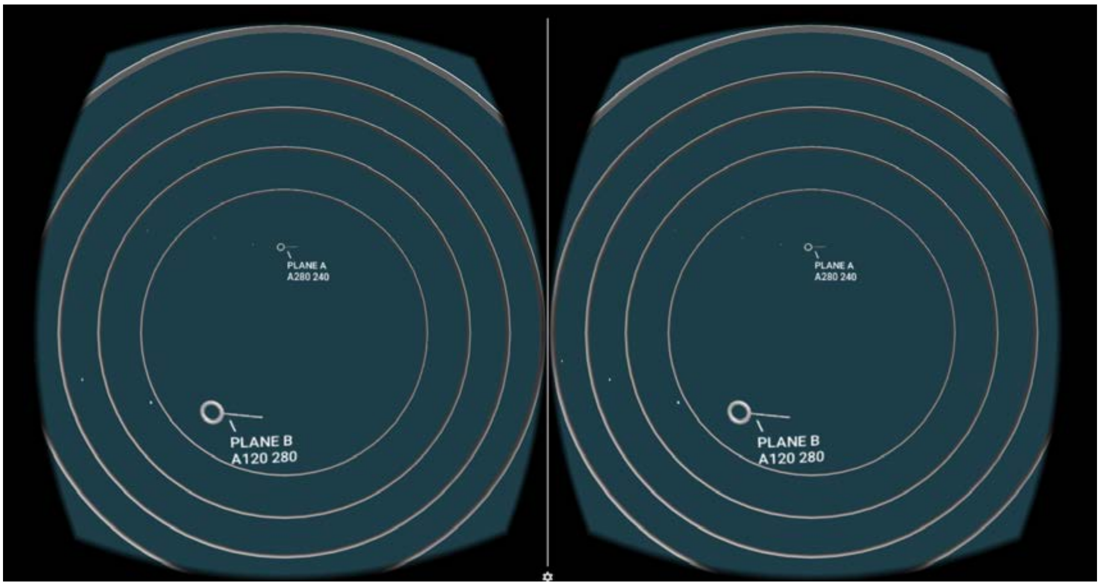

Figure 22. Screenshot of VR prototype 4

Second, the aircraft were positioned according to their respective flight altitude. The altitude information was also displayed. For example, A120 means altitude reading of 12000 feet. The higher the altitude, the further away the aircraft was from the camera. Aircraft with higher altitude would appear smaller than one with lower altitude readings (Figure 23).

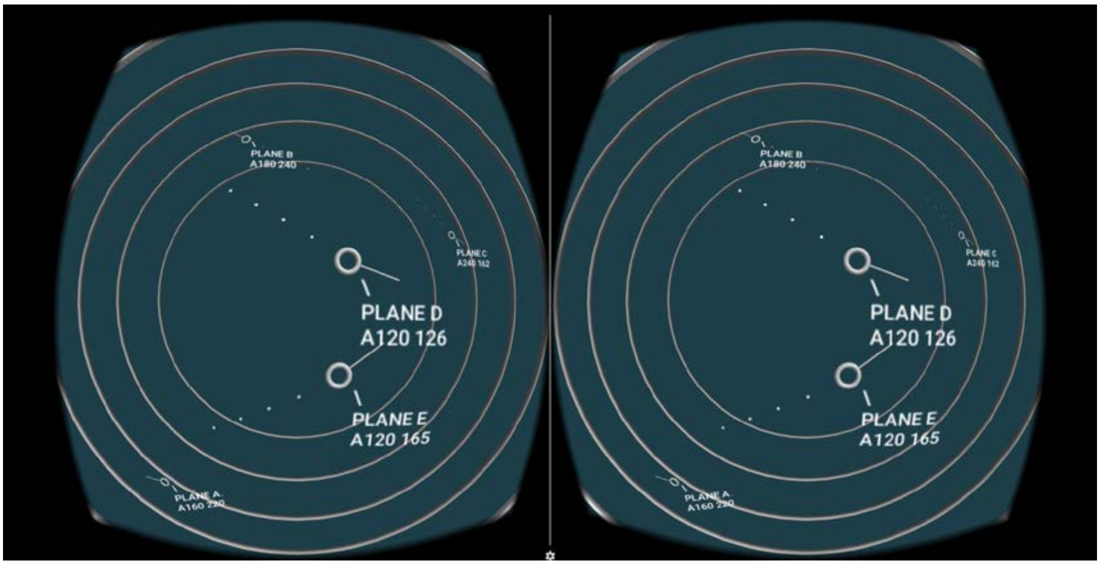

Figure 23. Distance between objects in VR prototype 4

Figure 24 is a screenshot captured from Unity3D perspective view. The size of the radar is 100 x 100 units in Unity3D and the camera is 50 units away from the radar. Each ring represents the same ring as in 2D visualisation, except the 3D visualisation was rendered in perspective view for VR device. Therefore shadows, lights, and distance of rings could be viewed.

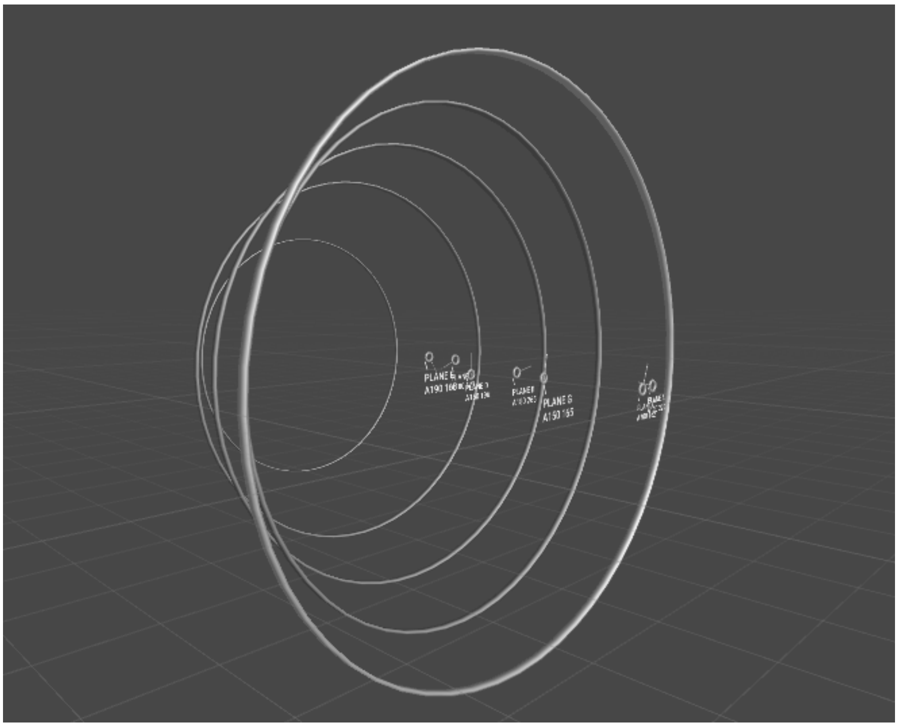

Figure 24. Screenshot of the perspective view in Unity3D

Figure 25 shows the details of aircraft, which contain flight information and radar symbols. In the perspective view of Unity3D, the aircraft represent the locations of the flights based on the flight plan design that was discussed in previous chapter. The final VR radar visualisation can be viewed online (https://youtu.be/fZGc8W2lxk4).

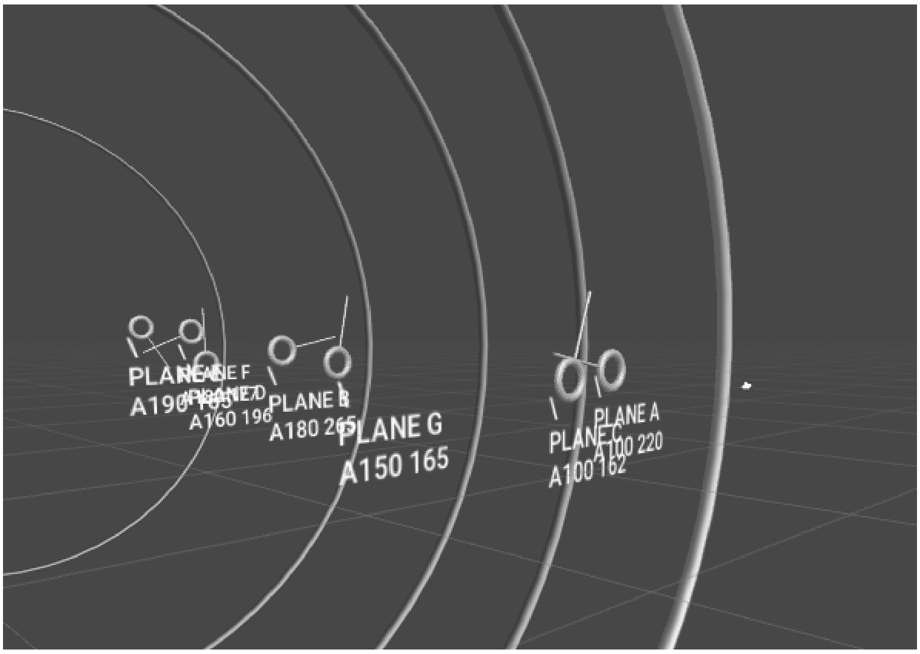

Figure 25. Detail of objects

4.2.2 Head-mounted Device

According to Hopkin (1995), tabular information display in 2D view is not effective at resolving the problem of heavy air traffic. This information has inspired the idea behind the current research as VR headsets would allow users to view a large data sets in an immersive environment.

At the start, the early prototypes were developed with Google VR for Android in Unity3D and tested with a VR headset (See Figure 26). The VR headset allows viewing Android VR application by inserting a smartphone into the headset. Unfortunately, feedback from users were not positive due to various issues. The VR headset was quite heavy. Some users also experienced light motion sickness due to the low framerate of the smartphone. It was hard to adjust the smartphone to the correct position. Last but not least, a smartphone based VR headset did not have positional tracking. Therefore, the final prototype was changed to an HTC Vive headset, which solved all these problems.

The HTC Vive offers sharper visuals and its sensors can map user's location within a room. It has several sensors such as gyroscope, accelerometer and laser position sensors. This effectively reads user's movements within the room space and allows the user to walk around the virtual scene (Fuchs, 2017, p. 64). This allow the participants to move forward and backward from the VR visualisation during the user test.

Figure 26. VR headset

4.3 Animations

The animations of history trail were created using the trail renderer function in Unity3D, which shows trails behind an object when it moves in the scene by generating particles behind, it also indicates what direction the object is heading and the speed of it (Lavieri, 2015, p. 139).

The history trail in both prototypes was visualised by white lines. In the second prototype development for both 2D and VR, red colour was added to represent arrival states and white colour represents departure states (Figure 27 & 28). It was noted that viewing flight information when there were many different departing and arriving flights at the same time was quite challenging.

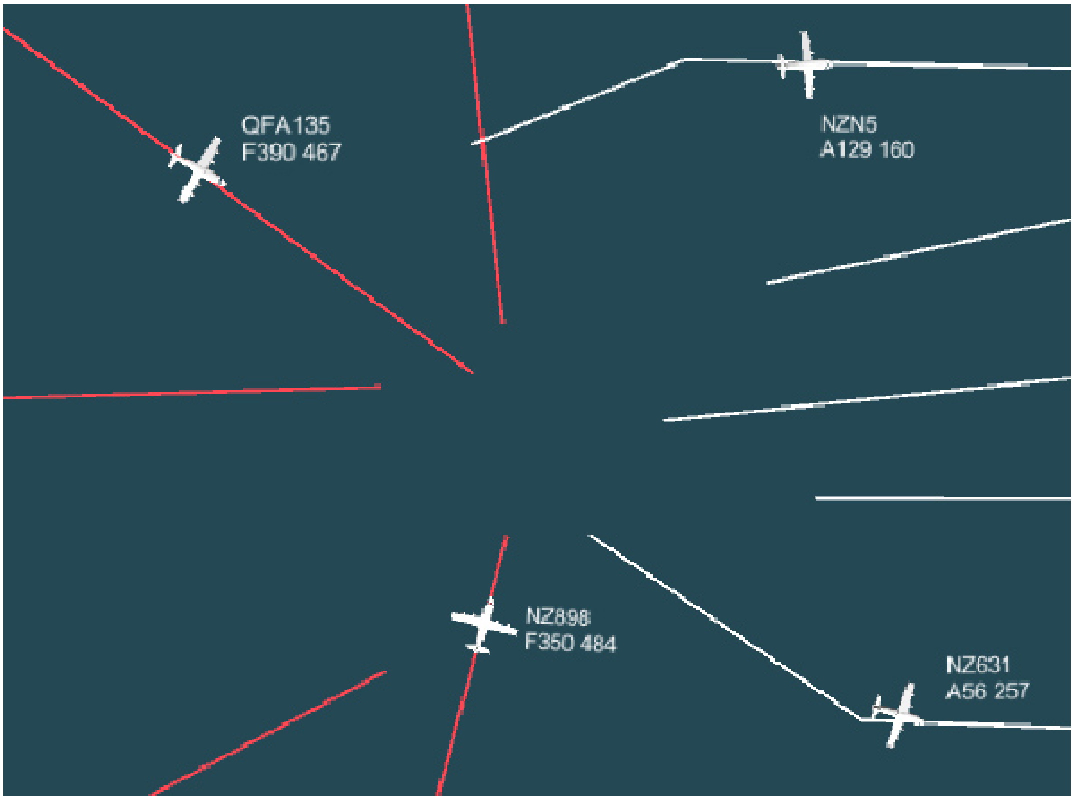

Figure 27. Departure and arrival lines in 2D version

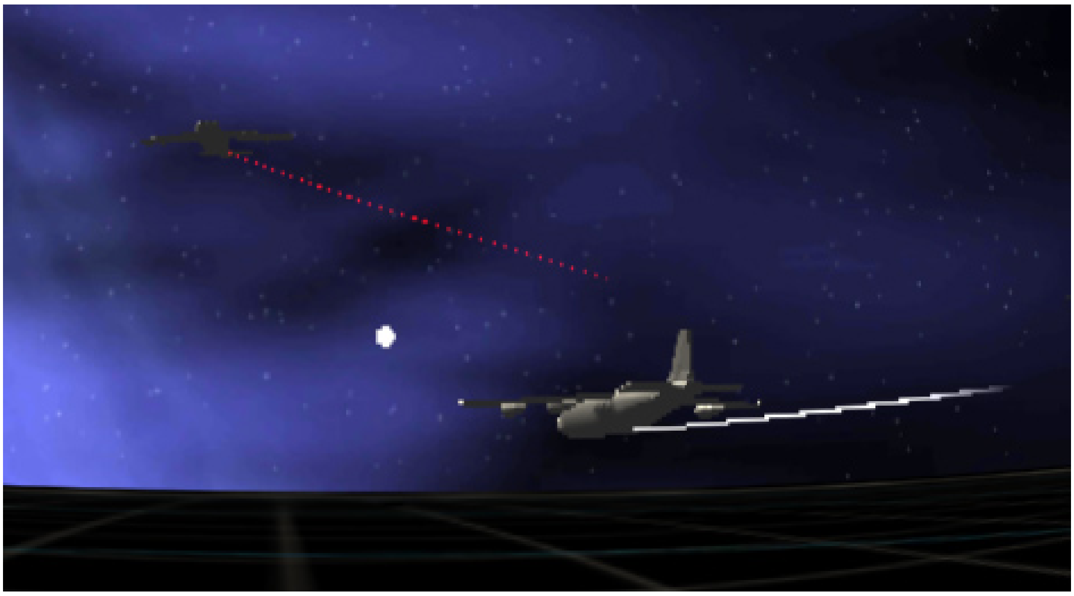

Figure 28. Departure and arrival lines in VR version

In the later development, only four white dots were used to indicate the history trail (Figure 29 & 30). Every moving aircraft would emit a white dot every second, with the maximum number of dots set at four, in alignment with standard commercial radar.

The altitude number was set in line with ATC safety program, which requires minimum separation distance between two aircraft to be 1000 feet vertically. The altitude numbers were programmed to refresh every ten seconds during the user test, similar to that of a commercial radar function. By refreshing altitude number every ten seconds, it encouraged users to pay attention to detailed flight information for decision making, instead of only looking at aircraft.

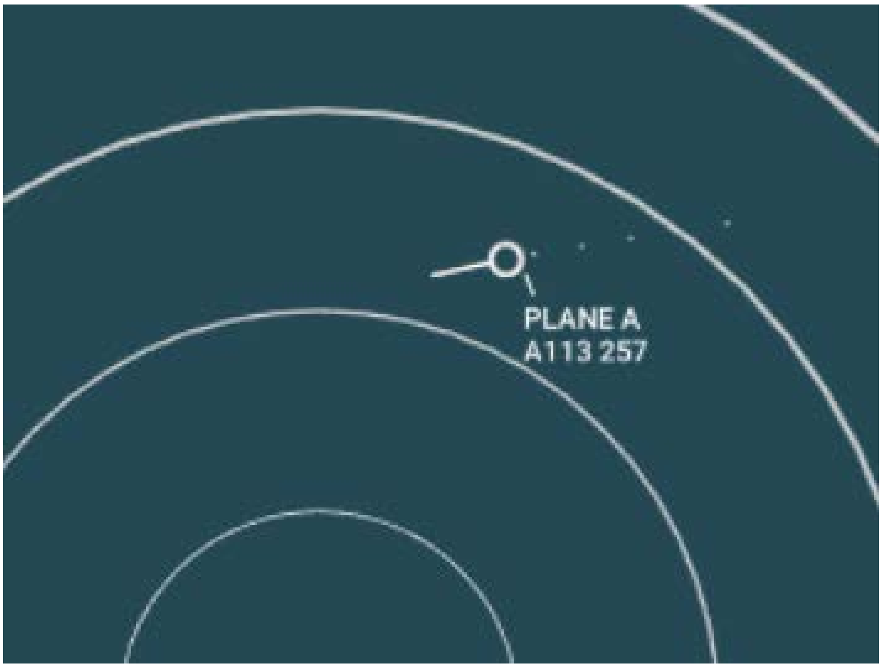

Figure 29. Detail of history trail in 2D version

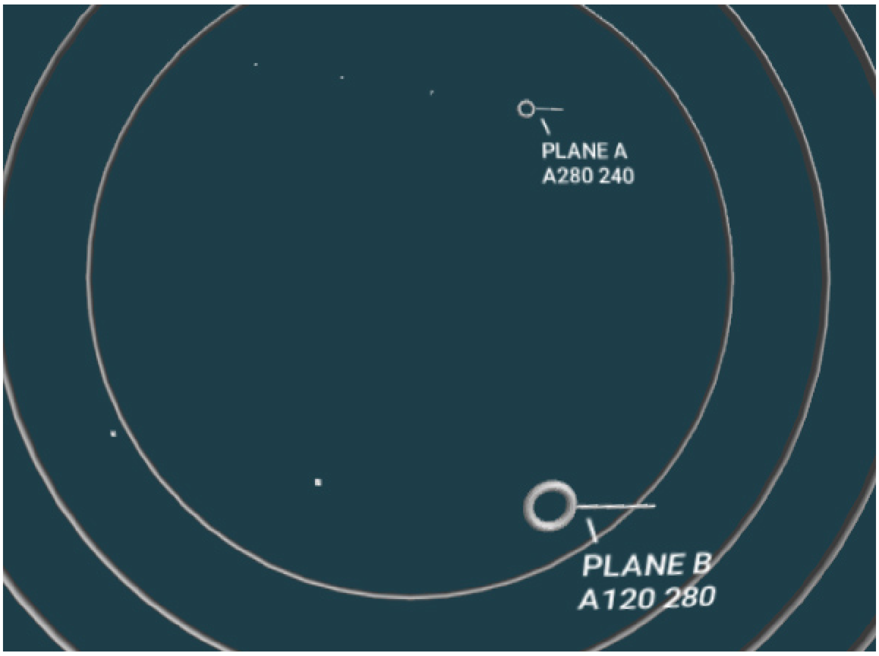

Figure 30. Detail of history trail in VR version

4.4 *Orthographic, Perspective and VR Environment Views*

The Unity3D game engine was used in simulating different scenarios in both 2D and VR visualisations. Both 2D and VR visualisations shared the same 3D models, distance setting of the camera, radar size, and light settings. There were five radar dials in the radar, the size difference between each radar dial was 20 units in Unity3D. The distance from camera to radar plane was 50 units, each radar dial was 20 units apart from each other.

The camera settings were different in 2D visualisation compared to the VR visualisation. The camera projection setting in the 2D visualisation was set to an orthographic projection (Figure 31). It effectively means viewing a three-dimensional object in perpendicular projection on 3D coordinate planes, where the object's original dimensions and shapes are unchanged, but without being able to view its depth (Wagh, 2014, p. 1842). In the 2D visualisation, the lines of radar dial remained white and flat in an orthographic view.

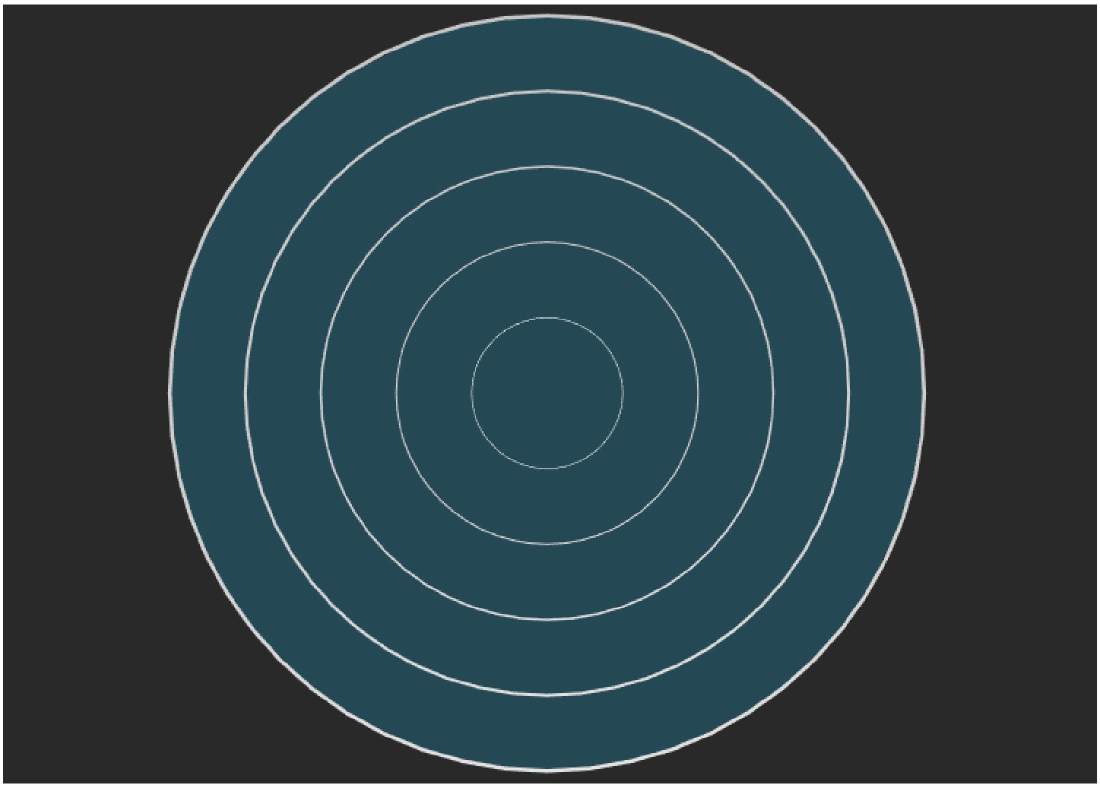

Figure 31. Orthographic projection in Unity3D

In VR version, the camera setting was set to perspective projection (Figure 32), which would allow participants to view using the HTC Vive headset. Compared to the 2D visualisation, navigating through a virtual environment generates a strong sense of presence. Moving through a virtual scene with head-tracking function generates a stronger sense of presence when it is controlled by users (Scherffig, 2016, p. 24). The HTC Vive headset includes a laser- based position tracking function that measures user's position as well as orientation within a physical space, which allows users to have bodily activities directly as to establish connections between action and spatial perception (Scherffig, 2016, p. 28).

In the VR visualisation, the lines of the radar dial are rendered with lights and shadows in perspective view. Therefore, when the aircraft overlap the radar dial, the shapes of aircraft and radar dial will not be distorted in perspective view.

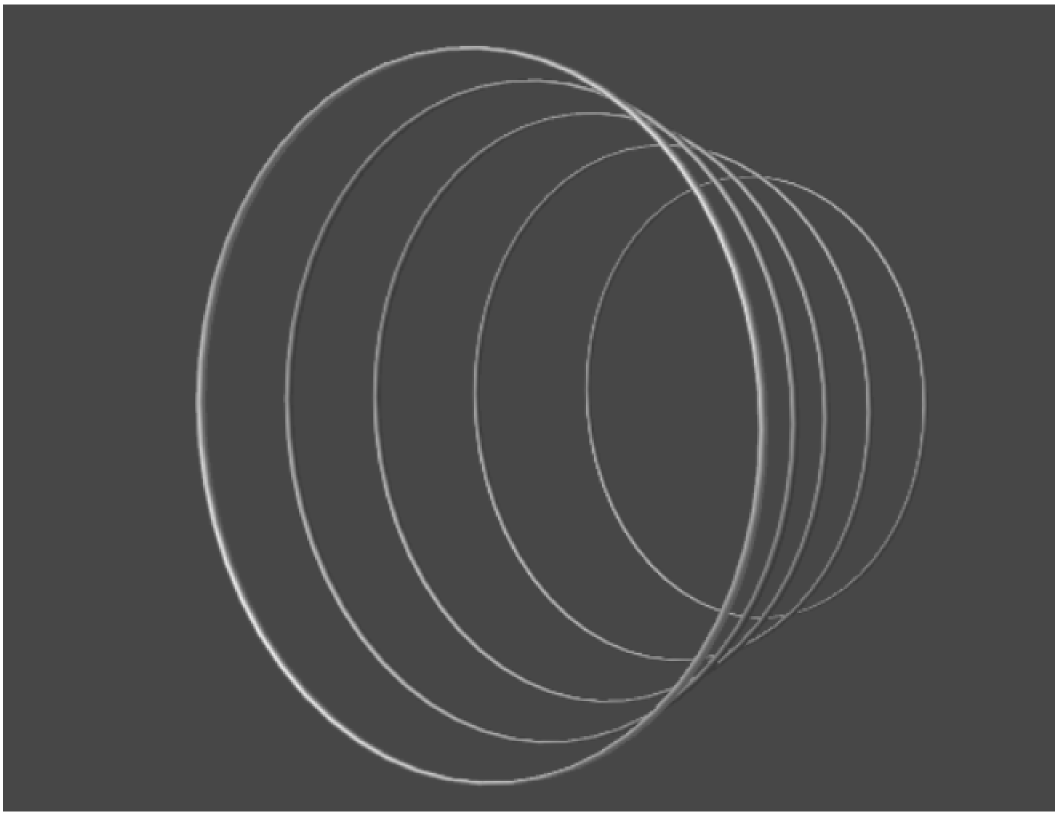

Figure 32. Perspective projection in Unity3D

4.5 Summary

With the objectives of obtaining useful data in user test, this chapter has outlined the implementation detail to support this study. The development paid attention to match the function of the existing commercial radar. Using different approaches of projections leads to useful results of human recognition of 3D and 2D objects interpretations, which includes testing with different VR devices, adjustment of animations as well as rendering settings. The user test results are presented in the results chapter.

5. Results

In the evaluation, synthetic ATC data was used to generate different scenarios of clean flights, near misses and collisions. Participants were invited to attempt to identify the scenario and both quantitative and qualitative data were collected to evaluate whether there is any statistically significant difference between the different visualisations in this chapter.

The results from user test data analysis can be used to provide insight to the underlying questions behind this research

1. Which visualisation is more suitable for understanding aircraft trajectories
2. Which visualisation is more suitable for identifying potential aircraft collisions

The following information was obtained from the participants.

Data logs

Data was captured every time a participant pressed the game control button, when he/she felt like a collision was about to occur. Four collision scenarios were designed in each of 2D and VR visualisation. Each collision was set at a specific time in scenario 2,4,5, and 6, and there is no collision in scenario 1 and 3. The data logging process also captured error counts, where a participant identifies an incorrect collision, and missed counts, where a participant misses a collision.

Qualitative Data

Qualitative data was captured during user tests, it includes comments from participants and observations of general reactions and movements from user tests.

Questionnaire Summary Findings

Questionnaire provides data about users' experiences and their preferences.

The information is analysed as follows:

Correlation Analysis

Correlation analysis was used to determine how the questionnaire data correlate to users' performances, to gain more insights to interpretations.

Comparative Analysis

Comparative analysis was conducted to compare data sets from the two visualisations, which included using statistical graphs of user detections and comparing them to actual collisions, as well as error and missed counts for both visualisations.

5.1 Participants

The user test was performed with the help of 15 participants. The invitations were in the form of email (Appendix 3) and posters (Appendix 4), aimed to attract university students. On the participant information sheet (Appendix 5), the participants were informed that they were free to withdraw from the research at any time without being disadvantaged in any way. Discomforts and risks were also mentioned on the participant information sheet as there might be a possibility that some people would not feel comfortable with VR devices. It also advised participants to stop immediately when experiencing physical discomfort during the user test. Subsequently, the participants were asked to fill in the consent form (Appendix 6). Moreover, all data collection would remain anonymous.

All participants had had previous VR experience. 11 of the users were male and 4 were female. The percentage of gender is presented in Figure 33. They were asked to test both the 2D display application and the VR application. When performing two tests, participants could have tendency to perform better in the second test as they apply the learnings obtained from the first test. Due to this reason, half of the participants started with the 2D display version followed by the VR version. The other half started with the VR version followed by the 2D version.

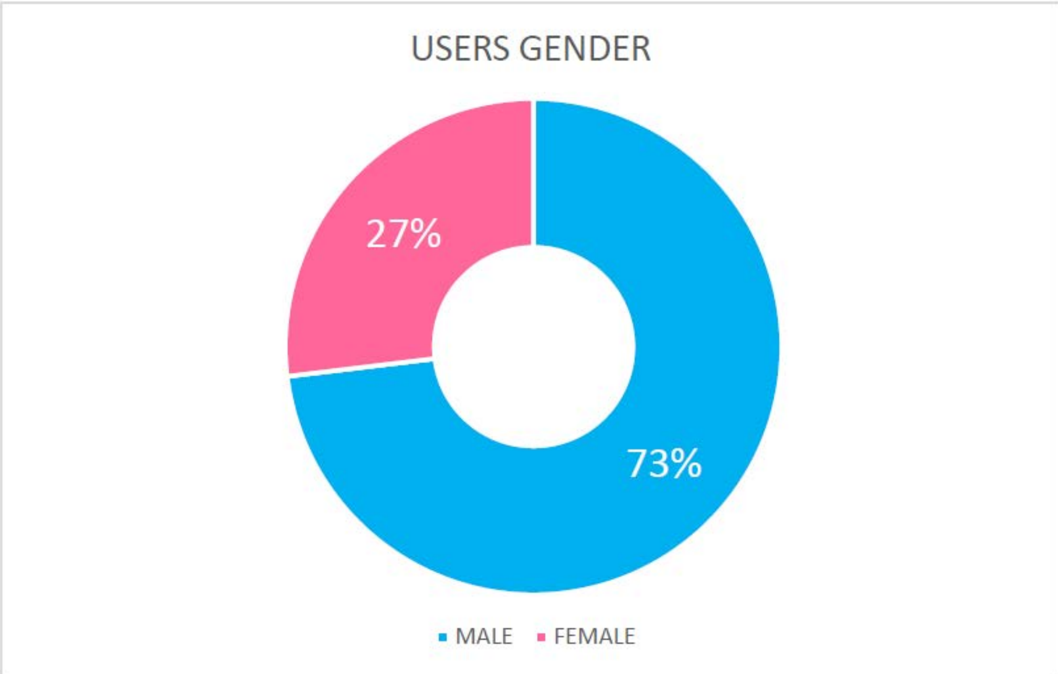

Figure 33. Gender percentage from 15 users

5.2 Data Logging

Figure 34 shows the data logs from the 2D application testing. Each colour represents an individual participant. On Axis Y, 0 is the time which actual collision occurred. Any bar graph below 0 indicates a “miss”, which effectively means participants failed to detect a collision. For example, user 2, 7 and 14 had a missed count record in collision 3. Bar graphs above 0 represent participants pressing the button before the actual collision happens. For example, user 8 pressed the button around 50 seconds ahead of the collision in scenario 4.

Figure 35 shows the data logs from the VR application testing. In collision 3, user 10 pressed the button 70 seconds ahead of the collision, whereas, in collision 4, user 2 had a missed count.

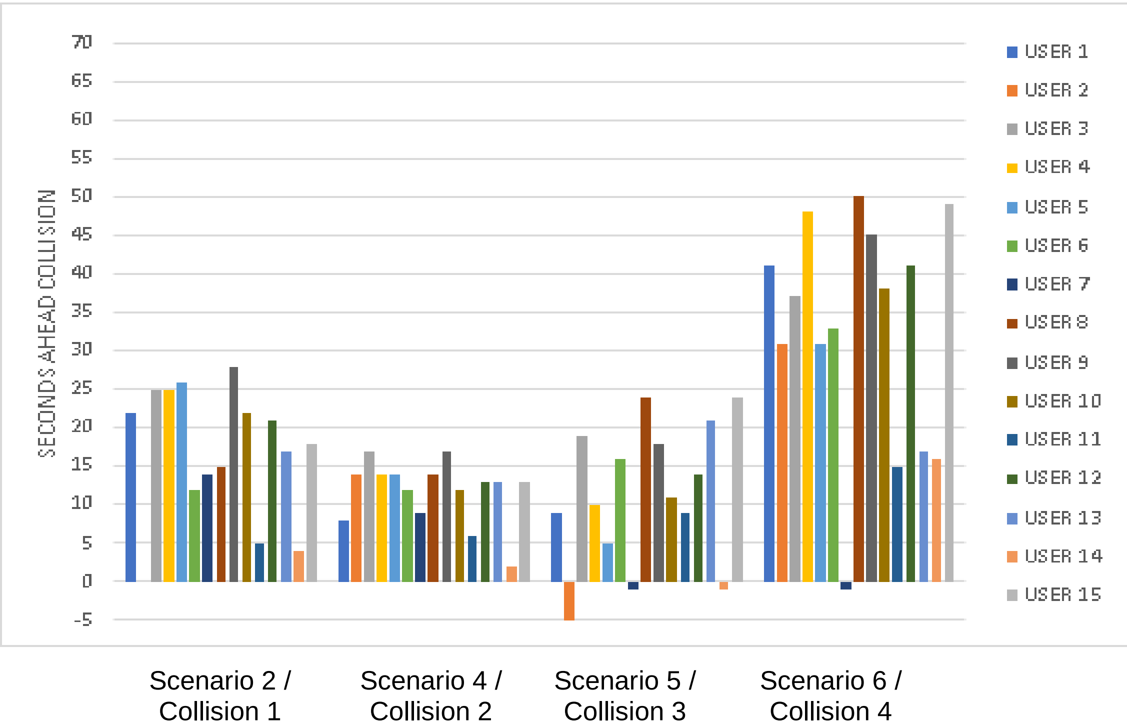

Figure 34. User test data logs from 2D application

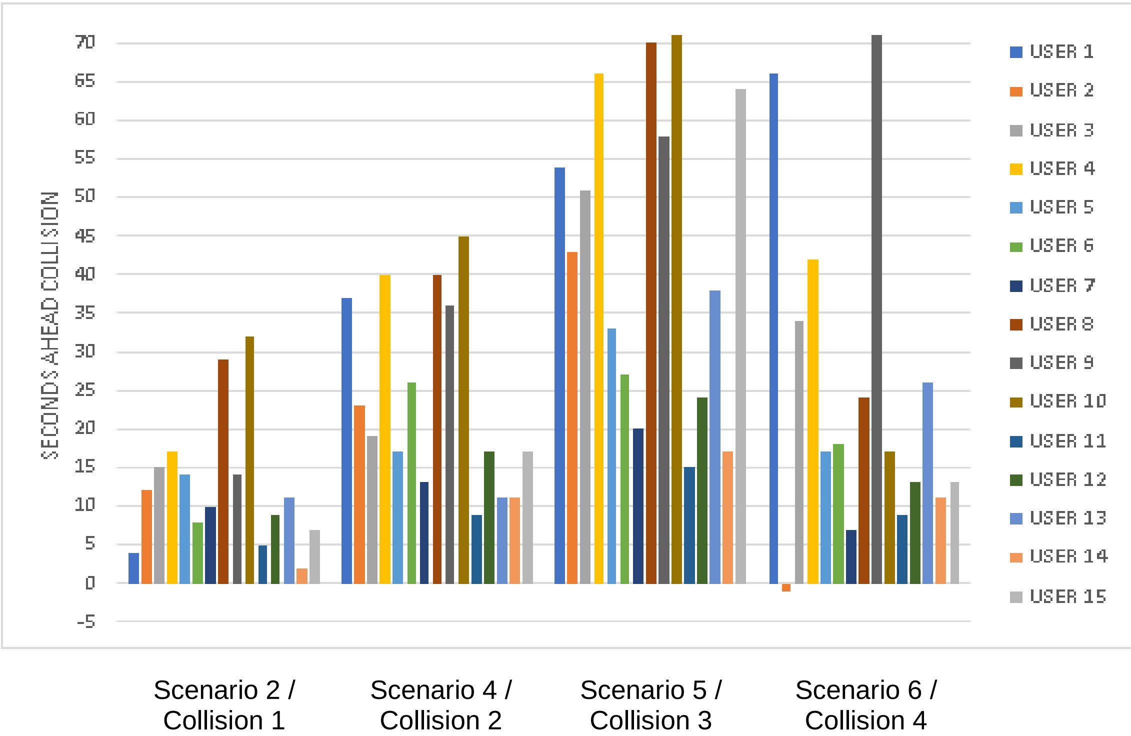

Figure 35. User test data logs from VR application

5.3 Qualitative Data

Note taking often provides more in-depth background and to remind an observer about the events, the descriptions of the field notes must be accurate and without bias (Yates & Leggett, 2016, p. 226).

The purpose of collecting qualitative data through observations is to document user behaviours and comments. Hence, during user tests, the participants were encouraged to make comments during the process of identifying collision. The most commonly mentioned comments include:

- VR gave a more real-world-like environment
- In VR, the participant was drawn to checking out size of objects, followed by checking altitude reading numbers. Using the2D display, the participant tended to focus on altitude readings only
- Looking at objects moving inside or out of the radar dial was helpful in VR application

- Depth and distance helped in identifying a possible collision
- Vision got blurred when the VR lens setting is incorrect

The most common behaviours of participants include:

- There were more head movements in VR testings
- Most had little or no hesitation when pressing game control button
- Participants observed more in VR testing environments followed by discussions of what they observed and found

5.4 Questionnaire Summary Findings

The questionnaire (see Appendix 7) contains 6 questions.

All participants are asked to rate the 2D and VR applications separately in question 1 to 4. For every question, participants are asked to give a rating of somewhere between 1 to 5. The results from the questionnaire for question 1 to 4 are summarised in Table 1 and 4.

Question 1: "To what extent did the visualisation give you a sense of scale and distance?". Participants would give answers ranging from 1 for "Poor" to 5 for "Excellent".

Table 1 *Descriptive statistics for question 1 in both applications*

Application	Average	Median
2D	3.2	3
VR	3.7	4

Question 2: “To what extent were you able to navigate in the visualisation?”. Participants would give answers ranging from 1 for “Barely” to 5 for “Easily”.

Table 2 *Descriptive statistics for question 2 in both applications*

Application	Average	Median
2D	3.9	4
VR	3.8	4

Question 3: “How easy was it for you to detect a possible collision?”. Participants would give answers ranging from 1 for “Hard” to 5 for “Easy”.

Table 3 *Descriptive statistics for question 3 in both applications*

Application	Average	Median
2D	3.5	3
VR	3.7	4

Question 4: “How often did you read the altitude and speed numbers in the visualisation?”. Participants would give answers ranging from 1 for “Not at all” to 5 for “Very often”.

Table 4 *Descriptive statistics for question 4 in both applications*

Application	Average	Median
2D	3.2	5
VR	3.7	5

In question 5, “When defining a possible collision, did the lights and shadows help to make a difference?”. Participants would give answers ranging from 1 for “Not at all” to 5 for “Definitely”.

Table 5 *Descriptive statistics for question 5 in both applications*

Average	Median
2.2	2

Figure 36 shows that more than half of the participants do not think the use of lights and shadows can help to make a difference while defining a possible collision.

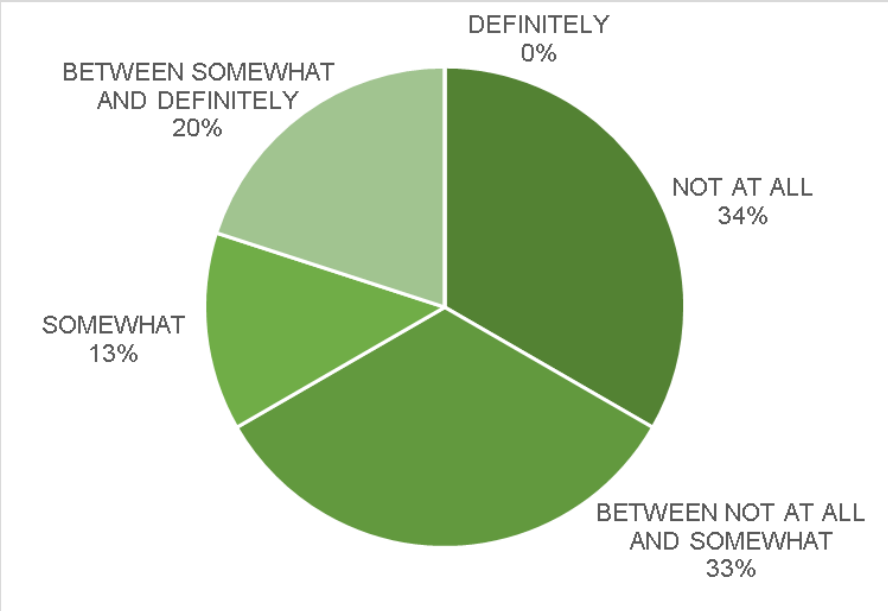

Figure 36. Participants' answers in question 5

For the last question, question 6, participants were asked “Which visualisation would you prefer for everyday use?”. Participants would select 1 for 2D, 3 for neither and 5 for VR.

In Figure 37, statistics show 13% of participants prefer neither application for everyday use. 20% of participants prefer VR application for everyday use and 14% of participants prefer 2D application for everyday use. 13% of participants prefer between VR and neither and 40% of participants prefer between 2D and neither.

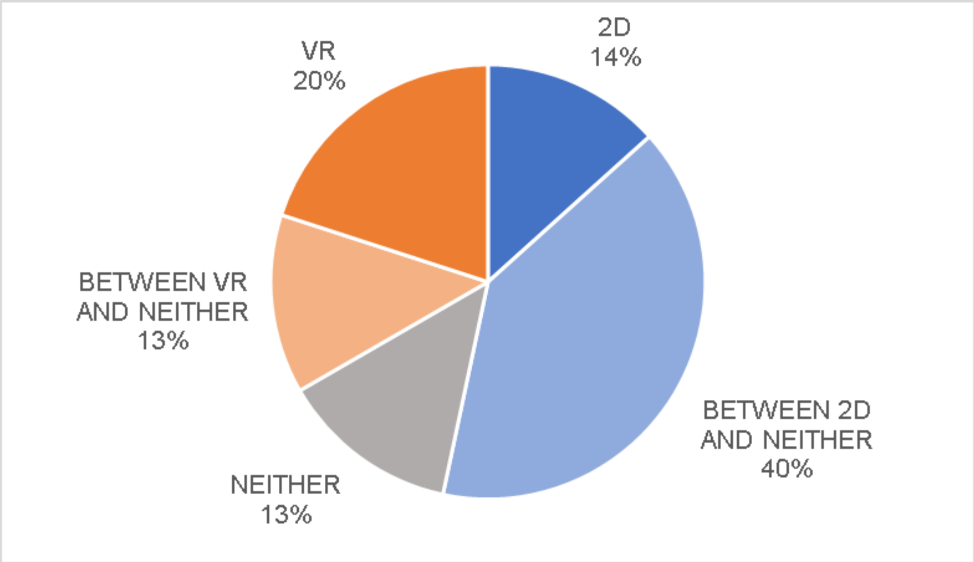

Figure 37. Participants' preferences in question 6

Based on the median scores of the responses obtained from question 1 to 4, the author would like to make a few quick observations. Participants perceive scale and distance better in VR than 2D application. Likewise, as for detecting possible collision, doing it in VR environment is slightly easier than 2D application. As far as navigation experience is concerned and how often participants read the altitude and speed number, the results are similar between both applications.

The responses to question 5 indicate that participants do not think the lights and shadows help to make a difference when defining a possible collision in both applications. And finally, based on responses obtained from question 6, more participants prefer VR visualisation for everyday use rather than 2D screen-based display.

To test the logical consistency between the responses collected on question 1 to 4 and detection performance of the participants, a correlation analysis has been performed to see if two variables are related. The analysis will be laid out in the next section.

5.5 Correlation Analysis

In this correlation analysis, the raw data from the questionnaire is attached in Appendix 8. Each graph demonstrates the correlation of individual user response for each question and their detection performance. Both variables will be presented in scatter plot. The purpose of this correlation analysis is to understand whether the participants’ scores match with their detection performance, and if a higher more favourable score translates into a better detection performance.

For question 1, "To what extent did the visualisation give you a sense of scale and distance?”. Figure 38 shows that 12 participants rated average to excellent in the 2D applications, and 13 participants rated average to excellent in the VR application. The linear trendline shows that the participants’ performances were faster in the VR application testing in general.

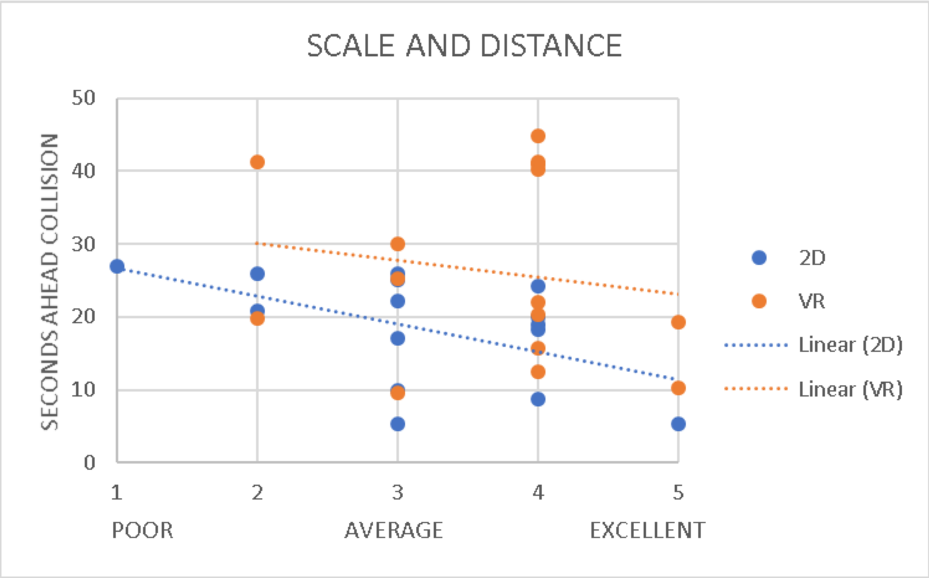

Figure 38. Correlation between scale and distance and user performance

For question 2, “To what extent were you able to navigate in the visualisation?”. Figure 39 shows that, except for one participant, all other participants rated above average for both applications. In a nutshell, almost all participants agree that it was easy to navigate in both applications. Interestingly, the linear trendline shows that the participants’ performances were faster in the VR application testing.

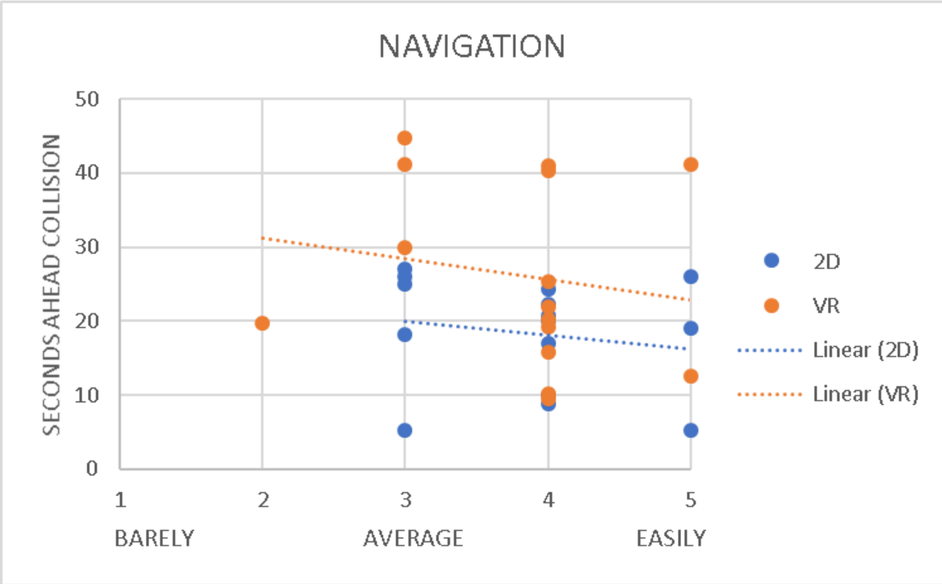

Figure 39. Correlation between navigation and user performance

For question 3, "How easy was it for you to detect a possible collision?". Figure 40 shows that 13 participants rated above average in the 2D application, and 14 participants rated above average in the VR application. Although the result of the ratings does not show a significant difference between the two applications, the error counts and missed out counts in the 2D application are greater than in the VR application testing (as shown in the comparative analysis section). The comparative results further indicate that even though participants generally feel it is easy to detect a possible collision in 2D environment, they did not perform so well on detecting the collisions in the said environment. Overall, the linear trendline shows that the participants' performances were faster in the VR application testing.

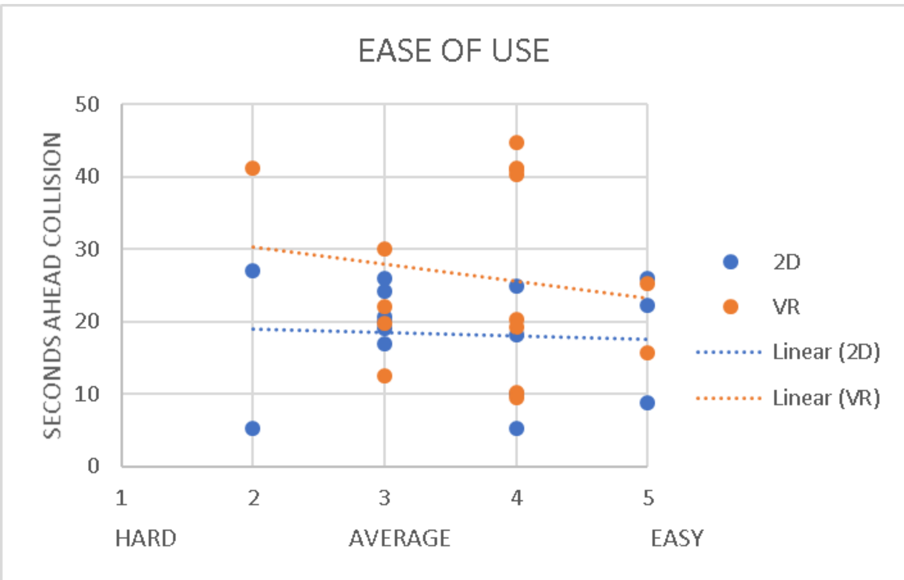

Figure 40. Correlation between ease of use and user performance

On question 4, “How often did you read the altitude and speed numbers in the visualisation?”. Figure 41 shows that most participants read the altitude and speed numbers quite frequently. 13 participants paid attention to readings in the 2D application, whereas 11 participants paid attention to readings in the VR application. The linear trendlines show a positive correlation between how often they read the numbers and how well they performed, in both 2D and VR applications. It is worth nothing that detection performance in the VR is better than the 2D application.

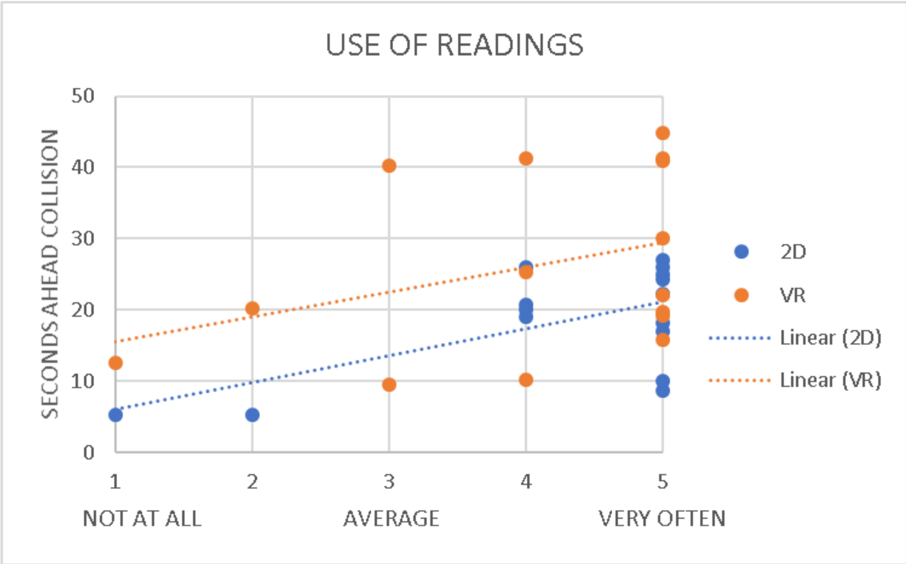

Figure 41. Correlation between use of readings and user performance

5.6 Comparative Analysis

The comparative analysis focuses on comparing user detections and actual collisions, in both 2D and VR visualisations. The results are presented in the form of box and whisker graphs as well as descriptive statistics.

Figure 42 shows the user detection time ahead of actual collision time in seconds, as well as numbers of missed counts in 2D application testing. The results are presented in the form of box and whisker graph.

In total, there are 5 missed counts in collision 1, 3 and 4 in 2D application testing. These missed counts are illustrated using the aircraft icons on the graph. Out of the 5 missed counts, 3 are in collision 3. The range and the interquartile range in collision 2 are the narrowest among the 4 collisions, and it has no missed count, which indicates the performance of the participants was more stable when identifying in collision 2.

Similarly, Figure 43 shows user detection time ahead of actual collision time in seconds, as well as numbers of missed counts, in VR application testing. The results are presented in a box and whisker graph.

In VR application testing, the only missed count was in collision 4. The range and the interquartile range are the narrowest in collision 1, which indicates the performance of the participants was more stable when identifying in collision 1. The range and the interquartile range are the highest in collision 3, which means the decision making and performance of participants were more varied during that experiment.

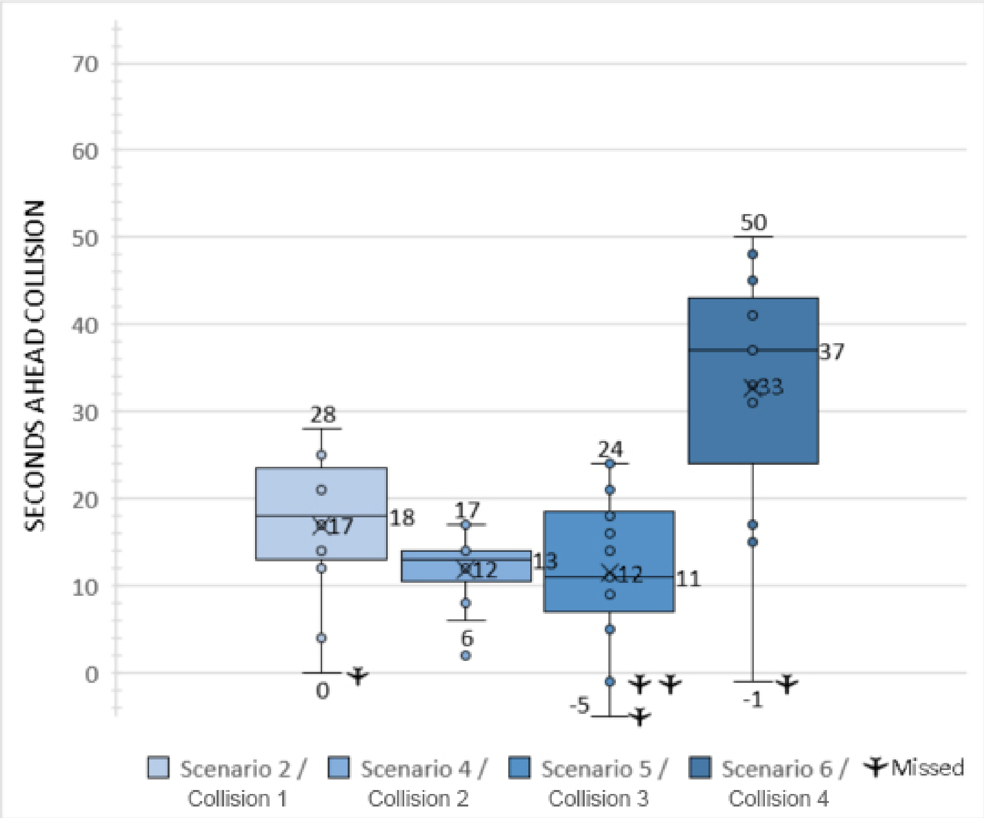

Figure 42. User detections compared to actual collisions in 2D application

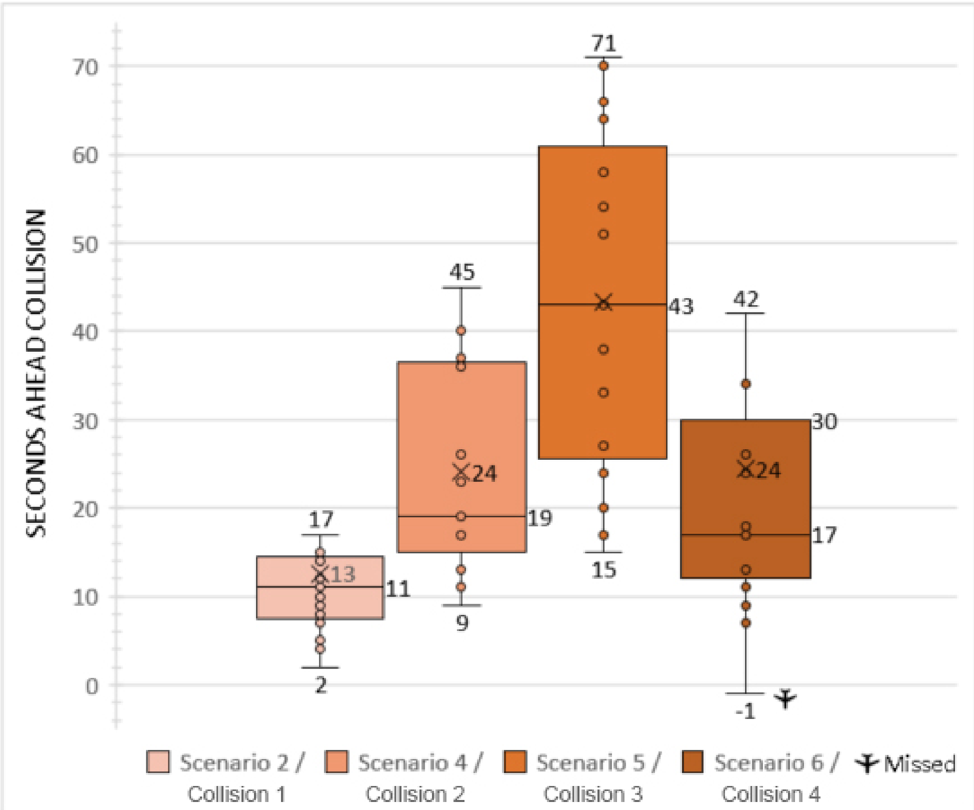

Figure 43. User detections compared to actual collisions in VR application

In comparison with collision 2 and 3 results in 2D application testing, user detection time in VR application testing was better in collision 2 and 3. On the other hand, user detection time is better in collision 1 and 4. Overall, the range and the interquartile range are narrower in 2D than VR application testing.

Descriptive data in Figure 42 and 43 is shown in Table 6 and 7.

Table 6 *Average seconds ahead collision descriptive statistics*

Collision	2D	VR
1	17	13
2	12	24
3	12	43
4	33	24

Table 7 *Median seconds ahead collision descriptive statistics*

Collision	2D	VR
1	18	11
2	13	19
3	11	43
4	37	17

Figure 44 compares side by side, the average of total seconds ahead collision for all 4 collisions, for 2D and VR visualisations. The average seconds of user detection ahead collision is 18 seconds in the 2D application, compared to 26 seconds in VR application. In other words, on average, the participants detected collision 8 seconds earlier in VR application than 2D application.

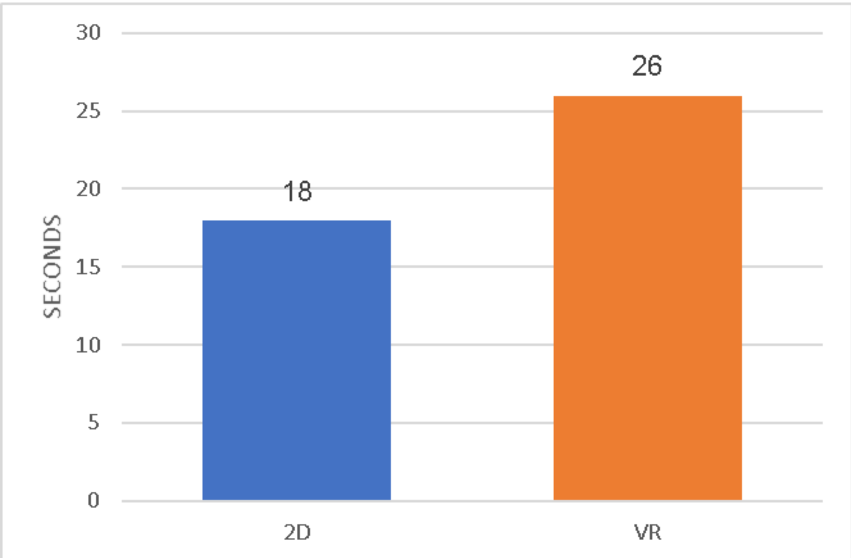

Figure 44. Average seconds ahead collision comparison

Figure 45 and table 8 show the error counts for both applications. This error counts were measured base on two scenarios, 1) when a participant presses the button and identifies an incorrect collision, 2) missed counts, where a participant misses a collision. The error count in 2D application is more than in VR application, at 21 versus 5. This is particularly evident in collision 3 and 4, where there are 9 and 6 error counts in 2D application compared to 1 each respectively in VR application. When the complexity of the scenario went up, except for collision 4, the error counts in 2D application increased from collision 1 to collision 3. Whereas in VR application, the error counts decreased obviously from collision 2 to collision 4.

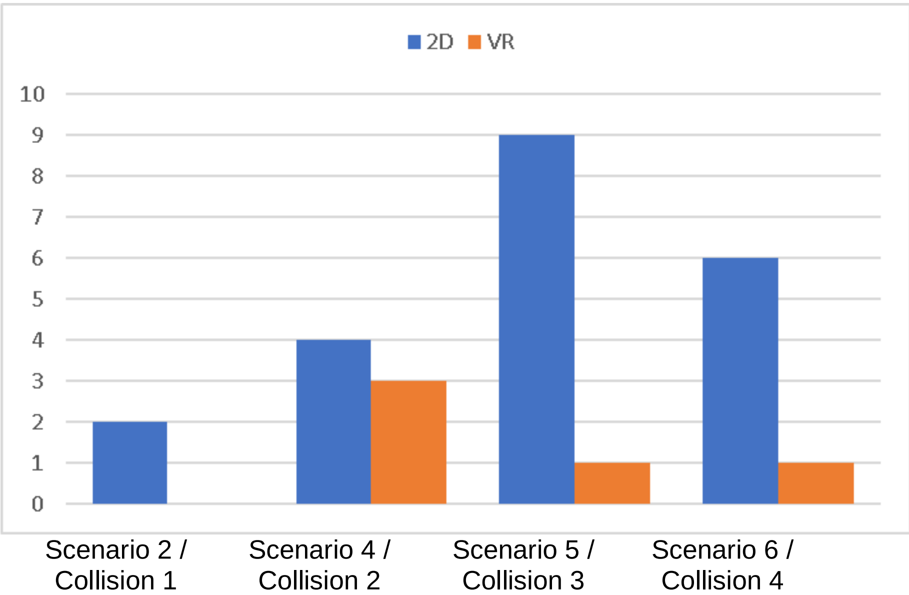

Figure 45. Error count

Table 8 *Total error count descriptive statistics*

Collision	2D	VR
1	2	0
2	4	3
3	9	1
4	6	1
Total	21	5

Figure 46 shows the total error count in percentage. Overall, the percentage of error count in 2D application testing is 26% and 8% in VR application testing. The high error count numbers in 2D applications indicates that participants might have possibly misinterpreted the information displayed in the 2D application, which resulted in incorrect judgment.

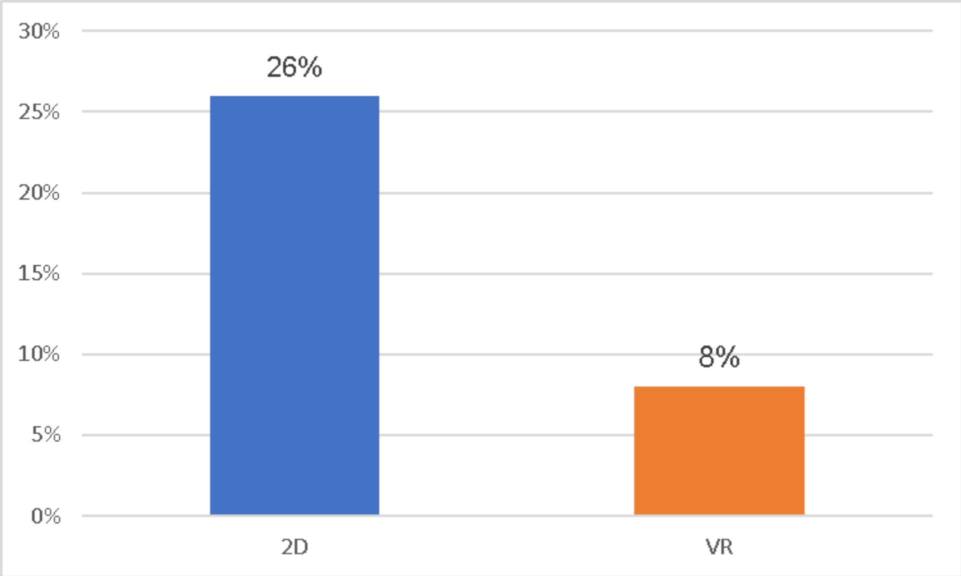

Figure 46. Total error count percentage

Based on the descriptive statistics in Table 9, Figure 47 shows the comparison of the missed count percentage in both applications. At over 30%, missed out count is markedly higher in the 2D application, compared to just over 5% in VR application.

Table 9 *Total missed count descriptive statistics*

Collision	2D	VR
1	1	0
2	0	0
3	3	0
4	1	1
Total	5	1

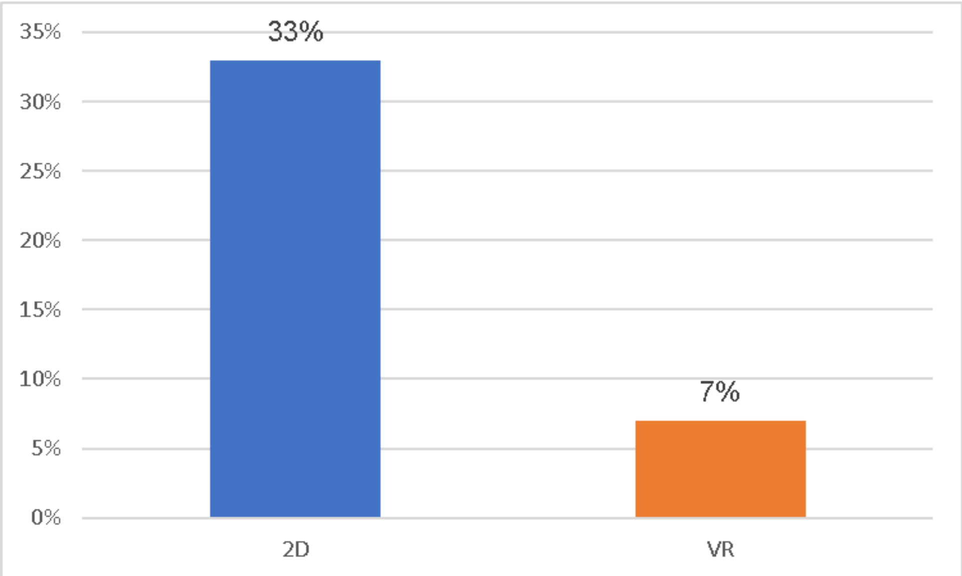

Figure 47. Missed count percentage comparison

6. Discussion

The primary objective of this study is to collect user test data for the purpose of evaluating the performance of VR technologies compared to traditional screen-based ATC visualisation technologies. The results discussed in this section assist in understanding the user performance in both applications.

In the qualitative data section, the comments from participants and user test observation were noted and recorded. Overall, VR applications gained more positive reviews. Participants preferred the real-world-like environment that VR was able to simulate. Depth and object sizes in VR applications were helpful when defining a possible collision. They also found it helpful to be able to look at objects moving inside or out of the radar dial.

In the questionnaire data analysis, participants felt that VR environment was more superior than 2D-based display, in terms of representing scale and distance. Participants also felt that it was easier to detect possible collision in the VR environment. Participants relied more on altitude reading in 2D application than in VR application. The reason was not entirely clear, but it could possibly be due to 2D environment having less details than the VR environment. There was no material difference in ease of navigation between the two applications, but overall, more participants preferred VR applications than 2D applications.

In the correlation analysis, the results further confirmed that participants performances were better in VR application testing. Moreover, there was a clear positive correlation between participants who read altitude and speed number and their positive performances. Reading the numbers seem to lead to better performance.

In the comparative analysis, there are three significant key findings. First, the average detection performance in the VR application testing is faster than the 2D application testing. Second, the error count in the 2D application is higher than in the VR application. Third, the missed count in the 2D application is higher than the VR application.

It is worth pointing out that the questionnaire responses from certain participants demonstrate some significant variations, where comparing their preferred application and their performance in their preferred application. To illustrate this point, please see Table 9 to 11 below.

Table 9 details the 5 possible answer options for user's preference in question 6 of the questionnaire form.

Table 9 *Options for users' preference in question 6*

2D	Between	Neither	Between	VR
1	2	3	4	5

Table 10 shows the user's preference along with their detection performance in both applications. The numbers are marked in green where user's preference match their performance, and in red where user's preference does not match their performance.

In summary, the user preferences of users 2, 4, 8, 9, 12, 14 and 15 match with their preferred application performance. The user preferences of users 3, 6, 7, 10, 11, and 13 however, do not match with their preferred application performance. And for those participants who opted for neither application for everyday use, user 1 and 5, their performances were better in VR application testing.

Table 10 *Users' preferences in question 6 compared to actual performance*

	Preference	2D	VR
USER 1	3	20	40
USER 2	5	10	19
USER 3	1	25	30
USER 4	4	24	41
USER 5	3	19	20
USER 6	1	18	20
USER 7	2	5	13
USER 8	5	26	41
USER 9	4	27	45
USER 10	2	21	41
USER 11	2	9	10
USER 12	2	22	16
USER 13	2	17	22
USER 14	5	5	10
USER 15	2	26	25

Related to Table 10, further analysis was performed, and the results summarised in Table 11 below.

There are 8 participants (user 3, 6, 7, 10, 11, 12, 13 and 15) who prefer "2D" and "Between neither and 2D", which is 54% of total 15 participants. 6 out those 8 participants performed better in VR application than in 2D application. The unmatched percentage is 75% for these participants who preferred 2D application.

There are 5 participants (user 2, 4, 8, 9 and 14) who prefer “VR” and “Between neither and VR”, which is 33% of total 15 participants. All of them performed better in VR testing, a 100% match rate.

Table 11 *Users' preferences and performance correlation percentage*

	Preference	Unmatched	Matched
2D	54%	75%	25%
NEITHER	13%		
VR	33%	0%	100%

Out of the 8 participants who expressed their preference for 2D application, only 2 performed better in 2D application test. The other 75%, 6 out of 8 participants, performed better in VR test.

7. Conclusions

There are two major underlying questions behind this research: When comparing a VR visualisation of air traffic with a 2D display-based application, which of the two

1) is more suitable for understanding aircraft trajectories?

2) is more suitable for identifying potential aircraft collisions?

Evaluation of the data and findings of this research has suggested that VR devices could potentially be a useful technology for ATC work. The user test results have shown positive encouraging statistics that the VR application was positively beneficial in enhancing the work of ATC and identifying potential aircraft collisions. The use of VR technologies has enhanced the information made available and improved user performance in detecting a potential collision with increased speed and better accuracy.

On further study of user preference versus user test performance, the analysis shows that a great majority of participants performed better in VR tests than 2D tests, including those who expressed their preference for using 2D technologies. 54% of the participants expressed their preference for 2D compared to 33% for VR, possibly due to the lack of familiarity with VR technologies. Despite that, 75% of those who preferred 2D technologies ended up performing better in VR tests compared to 2D tests.

And finally, the data analysis outcome provides effective results for VR user experiences related studies and will add potential insight in ATC industry in future development.

7.1 Design Guidelines

The use of new technologies is increasing rapidly. The current implementation of the applications focuses mainly on data visualisation techniques at Unity3D, flight path design, and user feedback. The design of current flight paths is limited to the six scenarios and aimed to avoid bias from each application.

Refinement could be made to advance algorithm design in this case, where random flight numbers and flight locations could be generated in each scenario. In this case, it would certainly create more scenarios to test. Further, the skybox settings in Unity3D could be customised, flight scenarios could be changed from day-time to night-time slowly in the visualisation, enabling data to be analysed from different aspects.

7.2 Limitations

The small number of participants is the main limitation in this study. To evaluate the user data with certain clarity, it is important to recruit more participants for the user test. Further, it could have been helpful to obtain eyesight information from the participants in the questionnaire from. This could ensure the results are based on similar eyesight condition.

Another limitation is that the study only incorporated participants who are not air traffic controllers. Given the relatively stringent requirements on spatial information processing in the selection process of air traffic controllers, it is possible that different results may result from a study involving fully trained air traffic controllers.

7.3 Future Research Implications

Human-centered design and interactions are also important in this evaluation. Future work could potentially focus on these directions. Some potential features could be tested for further insights, such as voice command and interaction features. This would help to improve the variety of data collections and possibly resolve specific conflicts. And clearly, the paper strip function is not the focus in the current study. Conceptually, it could be beneficial to look at integrating the paper flight strip with the VR device, as it could have the potential to transform the working practice of Air Traffic Controllers and integrate VR into their working environment in the future.

As the participants performance are variable, refinements can be made to the participant recruitment in later research. User experience in air traffic visualisation ideally test with air traffic controllers can inform future research and resolve specific questions.

7.4 Concluding Remarks

This research has evaluated the human performance on the data visualisation technologies for air traffic control with a 2D data visualisation on screen and a VR data visualisation. Two data radar visualisations were developed for participants to detect collisions during the user test. Participants' detection performances were captured, and their user experience were rated in questionnaire forms.

Although there was not a significant finding in part of the data analysis due to the number of participants were not as many as required. Results have shown that the participants' favour in questionnaire forms are variant. However, the detection performance in VR application was better than 2D application. It seems that the participants who preferred VR device were comfortable to complete the user tasks.

Furthermore, there have been studies suggest that 3D visualisation and virtual environments can enhance the effectiveness of data analysis as well as to discover new behaviours and knowledge.

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Glossary

2D display - A rectangular display device that displays graphics in pictorial form.

3D stereoscopic - A technique which incorporates new technologies, it allows human to sense a greater depth in an image.

3D visualisation - A graphical content that is generated using 3D software and a variety of technologies.

Air traffic control - Air traffic control provides service to aircraft operating within airspace and support information for pilots. The main purpose of Air traffic control is to organise the air traffic flow and to prevent collisions.

Alphanumeric screen - A combination of alphabetic and numeric characters.

First-person - A first-person perspective is usually used in avatar-based game, wherein the player's avatar would view with the player's own eyes and the player usually cannot see the avatar's body.

Immersive - A three-dimensional image which generated by a computer display. The image appears to surround the user that they feel involved in it.

Orthographic projection - A method of representing a three-dimensional object in two-dimension by using parallel lines to project its outline onto a plane.

Skybox – A skybox setting at Unity3D is a panoramic view, which splits into six textures representing six different directions along the main axes (up, down, left, right, forward and backward). The six texture images will fit together at the edges to create a continuous surrounding image that can be viewed from "inside" from any direction.

Tabular information display – A tabular presentation or a table is a data structure that allows to display information into rows and columns or a more complex structure.

Trajectory - A route or a path that a flying object follows through space as a function.

VR - Virtual reality is the use of computer technology that simulates human's physical presence in an immersive environment.

Appendices

Appendix 1: List of data obtained during user tests

User data log in 2D application testing

		Collision 1		Collision 2			Collision 3			Collision 4
Actual collision time		90		240			330			460
USER 1	57	68	230	232		316	321			419
USER 2		90		226			335			429
USER 3		65		223		308	311			423
USER 4		64		228			320			412
USER 5		64	198	226		287	325	361	394	429
USER 6		78		228			314			427
USER 7		76	226	231	285	319	331		379	461
USER 8	53	75	198	226	286	290	306		406	410
USER 9		62		223		308	312		409	415
USER 10	54	68		228		266	319		353	422
USER 11		85		234			321			445
USER 12		69		227			316			419
USER 13		73		227			309			443
USER 14		86		238		293	331		440	444
USER 15		72		227			306			411

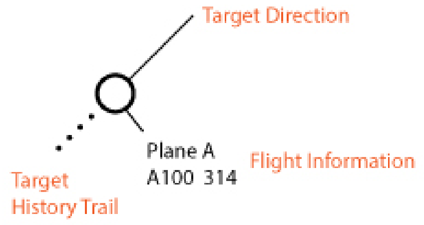
User data log in VR application testing

	Collision 1		Collision 2	Collision 3		Collision 4
Actual collision time	75		215	305		425
USER 1	71		178	251		359
USER 2	63		192	262		426
USER 3	60		196	254		391
USER 4	58		175	239		383
USER 5	61	104	198	272		408
USER 6	67		189	278		407
USER 7	65	108	202	285		418
USER 8	46		175	235		401
USER 9	61		179	247		354
USER 10	43		170	234	356	408
USER 11	70		206	290		416
USER 12	66	196	198	281		412
USER 13	64	103	204	267		399
USER 14	73		204	288		414
USER 15	68		198	241		412

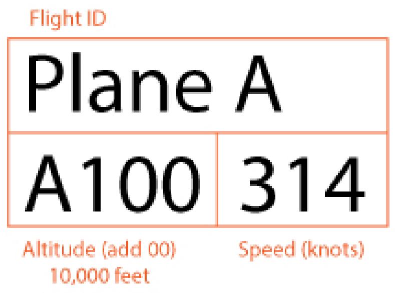
Appendix 2: List of user instruction

USER INSTRUCTION

RADAR SYMBOL



FLIGHT INFORMATION



Appendix 3: Research participants invitation

Research Participation Invitation

Evaluation of Data Visualisation Technologies for Air Traffic Control

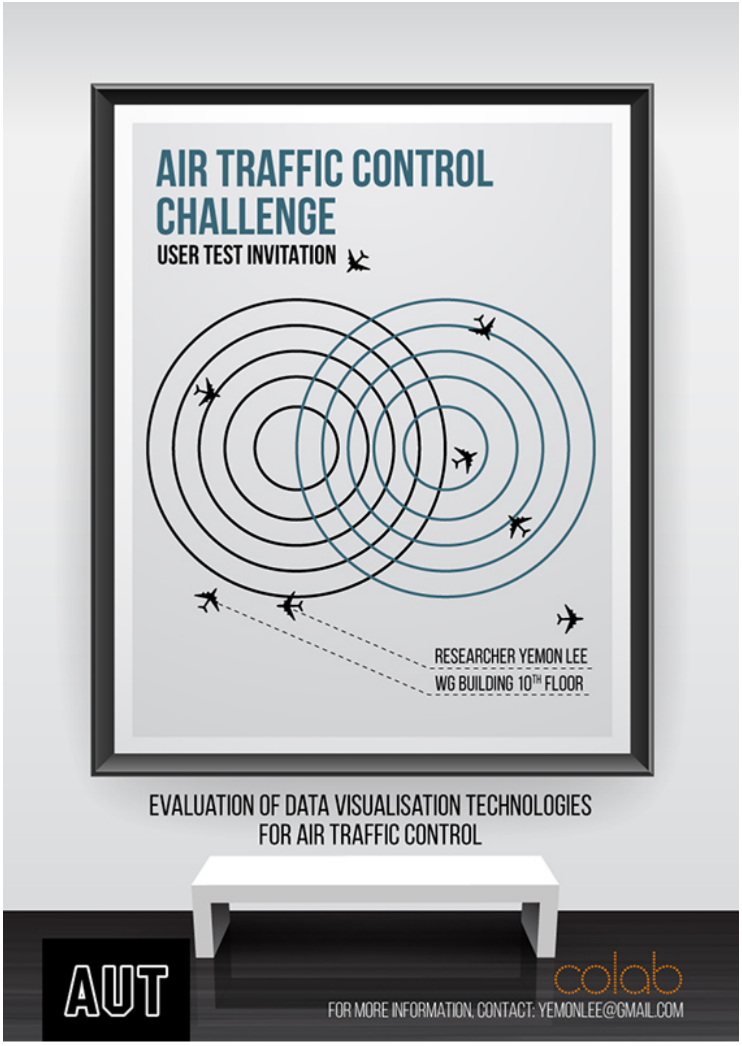
We are currently undertaking research that compares traditional 2D data visualisation with virtual reality (VR) data visualisation in the context of air traffic control. To help us do this, we would like you to experience the two different applications and provide feedback. The study data will be used in a Masters project entitled “Evaluation of Data Visualisation Technologies for Air Traffic Control” at Colab, Auckland University of Technology (*AUT*), New Zealand.

In order to participate in this research study, you must have had previous user experience with VR devices such as Oculus Rift, HTC Vive or watching a 360-degree video with head mounted device.

If you are interested in participating in this study, please contact Yemon Lee before **29th August 2017** by emailing to yemonlee@gmail.com. We will then send you a detailed information sheet outlining what will be requested of you during the study.

This project has been approved by the Auckland University of Technology Ethics Committee on 8th August 2017, AUTEC’s Ethics Application number is 17/257. If you have any questions regarding your rights as a participant, please contact Auckland University of Technology Ethics Committee (AUTEC) faculty representative by telephone on 921 9999 at extension 6831.

Appendix 4: Poster for user test invitation



Appendix 5: Participant information sheet

Participant Information Sheet

Date Information Sheet Produced:

31st July 2017

Project Title

Evaluation of Data Visualisation Technologies for Air Traffic Control

An Invitation

My name is Yemon Lee and I am a Master student at Auckland University of Technology (AUT). I am currently undertaking research that compares traditional 2D data visualisation with virtual reality (VR) data visualisation in the context of air traffic control

You are being invited to take part in this research study. Your participation in this study is completely voluntary and you can withdraw from this study without explanation, provided your request is received no later than August 25th, 2017. You also have the right to withdraw retrospectively any consent given, and to require that any data gathered on you be destroyed. If you are a student at AUT then a decision not to participate will not affect your grades or work performances in any way.

The results of this research study will be used for my Master research. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take as much time as you would like to read this information carefully.

What is the purpose of this research?

The aim of this study is to investigate approaches for combining VR technologies with data visualisation using a specific case study relating to air traffic control data and to discover their influence on the process of understanding data. This research will investigate the potential to detect collisions through the use of immersive VR visualisation and to compare this VR visualisation with traditional 2D visualisation. The use of VR technologies in air traffic control field of study may provide answers to whether if VR can enhance humans' ability in collision detection effectively than the 2D visualisation. Please remember that your responses are used to evaluate the implementation of the visualisations, they are not used to evaluate you as an individual.

How was I identified and why am I being invited to participate in this research?

You were chosen, along with 10 others, because you have indicated your interest in participating in the study by responding to an invitation circulated through groups with a direct interest in VR development.

How do I agree to participate in this research?

If you decide to take part in this research study, you will be asked to sign a consent form on the day of study.

Can I withdraw from this research?

You may withdraw yourself or any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

What will happen in this research?

You will be asked to observe air traffic using the two different visualisations. This will be for a maximum of 45 minutes overall. You will be asked to look out for possible flight collisions in both visualisations. Your inputs and detection times will be recorded and analysed in the research later. No other data is collected during the observation of your user test. Upon finishing the user test, you will be asked to complete a questionnaire that will ask you questions related to your user experience.

What are the discomforts and risks?

Some people who do not use VR hardware regularly may find that the use of VR is uncomfortable and may lead to dizziness, disorientation, and/or nausea.

How will these discomforts and risks be alleviated?

If you experience any onset of physical discomfort during the user test, you are advised to stop immediately and have the opportunity to either rest for a while and then continue, or to withdraw from the study.

What are the benefits?

There are no tangible benefits to you for participating in this research study other than the opportunity to test the application and to contribute to the development of future applications that have the potential to improve air traffic safety.

How will my privacy be protected?

Any data collected in this research study will remain confidential. Any analysis of results that would be published will be anonymous.

What are the costs of participating in this research?

The study will only require 30-45 minutes of your time to complete the user test.

What opportunity do I have to consider this invitation?

Since this research study involves spending up to 30-45 minutes to complete the user test and questionnaire, the researcher understands that it requires time for you to consider whether you wish to participate. The researcher will appreciate if you could send a reply within two weeks of the receipt of this form.

Will I receive feedback on the results of this research?

If you wish to receive a final report of the experimental findings or publications through email, the results are likely to be completed in December 2017.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Dr. Stefan Marks, stefan.marks@aut.ac.nz and Tel: +64 9 921 9999 extension 5028.

Concerns regarding the conduct of the research should be notified to AUTEC, Kate O'Connor, ethics@aut.ac.nz, Tel: +64 9 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Yemon Lee, yemonlee@gmail.com

Project Supervisor Contact Details:

Dr. Stefan Marks, stefan.marks@aut.ac.nz and Tel: +64 9 921 9999 extension 5028

Address: Colab (D60), Private Bag 92006, Auckland 1020, New Zealand.

Approved by the Auckland University of Technology Ethics Committee on type the date final ethics approval was granted, AUTEC Reference number type the reference number.

Appendix 6: Consent Form

Project title:

Evaluation of Data Visualisation Technologies for Air Traffic Control

Project Supervisor: ***Dr. Stefan Marks***
Researcher: ***Yemon Lee***

○ I have read and understood the information provided about this research project in the Information Sheet dated / /2017.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○ I agree to take part in this research.

Participant’s signature: ....

Participant’s name: ....

Date: ....

I wish to receive a copy of the final report from the research:

○ Yes, my Email or Postal address is: ....

○ No

Approved by the Auckland University of Technology Ethics Committee on 8th August 2017, AUTEC Reference number 17/257.

Appendix 7: Questionnaire for participants

Participation Questionnaire

Evaluation of Data Visualisation Technologies for Air Traffic Control

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

1. To what extent did the visualisation give you a sense of scale and distance?

2D:	O 1	O 2	O 3	O 4	O 5
	Poor		Average		Excellent
VR:	O 1	O 2	O 3	O 4	O 5

2. To what extent were you able to navigate in the visualisation?

2D:	O 1	O 2	O 3	O 4	O 5
	Barely		Average		Easily
VR:	O 1	O 2	O 3	O 4	O 5

3. How easy was it for you to detect a possible collision?

2D:	O 1	O 2	O 3	O 4	O 5
	Hard		Average		Easy
VR:	O 1	O 2	O 3	O 4	O 5

4. How often did you read the altitude and speed numbers in the visualisation?

2D:	O 1	O 2	O 3	O 4	O 5
	Not at all		Average		Very Often
VR:	O 1	O 2	O 3	O 4	O 5

5. When defining a possible collision, did the lights and shadows help to make a difference?

O 1	O 2	O 3	O 4	O 5
Not at all		Somewhat	Definitely	

6. Which visualisation would you prefer for everyday use?

O 1	O 2	O 3	O 4	O 5
2D		Neither		VR

Appendix 8: Questionnaire data

Question 1:

To what extent did the visualisation give you a sense of scale and distance?

	SCORE FOR 2D	SCORE FOR VR
USER 1	4	4
USER 2	3	5
USER 3	3	3
USER 4	4	4
USER 5	4	4
USER 6	4	2
USER 7	5	4
USER 8	2	4
USER 9	1	4
USER 10	2	2
USER 11	4	3
USER 12	3	4
USER 13	3	4
USER 14	3	5
USER 15	3	3

Question 2:

To what extent were you able to navigate in the visualisation?

	SCORE FOR 2D	SCORE FOR VR
USER 1	4	4
USER 2	4	4
USER 3	3	3
USER 4	4	5
USER 5	5	4
USER 6	3	2
USER 7	5	5
USER 8	3	4
USER 9	3	3
USER 10	4	3
USER 11	4	4
USER 12	4	4
USER 13	4	4
USER 14	3	4
USER 15	5	4

Question 3:

How easy was it for you to detect a possible collision?

	SCORE FOR 2D	SCORE FOR VR
USER 1	3	4
USER 2	4	4
USER 3	4	3
USER 4	3	4
USER 5	3	4
USER 6	4	3
USER 7	4	3
USER 8	3	4
USER 9	2	4
USER 10	3	2
USER 11	5	4
USER 12	5	5
USER 13	3	3
USER 14	2	4
USER 15	5	5

Question 4:

How often did you read the altitude and speed numbers in the visualisation?

	SCORE FOR 2D	SCORE FOR VR
USER 1	4	3
USER 2	5	5
USER 3	5	5
USER 4	5	5
USER 5	4	2
USER 6	5	5
USER 7	1	1
USER 8	5	5
USER 9	5	5
USER 10	4	4
USER 11	5	3
USER 12	5	5
USER 13	5	5
USER 14	2	4
USER 15	4	4

Question 5:

When defining a possible collision, did the lights and shadows help to make a difference?

	SCORE
USER 1	4
USER 2	2
USER 3	1
USER 4	1
USER 5	2
USER 6	1
USER 7	2
USER 8	4
USER 9	1
USER 10	1
USER 11	4
USER 12	3
USER 13	2
USER 14	3
USER 15	2

Question 6:

Which visualisation would you prefer for everyday use?

	SCORE
USER 1	3
USER 2	5
USER 3	1
USER 4	4
USER 5	3
USER 6	1
USER 7	2
USER 8	5
USER 9	4
USER 10	2
USER 11	2
USER 12	2
USER 13	2
USER 14	5
USER 15	2