UNIVERSITY OF CANTERBURY

3D Multi-user Interactive Visualization with A Shared Large-scale Display

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A thesis submitted in partial fulfillment of the requirements
for the Degree of Doctor of Philosophy
in the University of Canterbury

By

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Abstract

When the multiple users interact with a virtual environment on a large-scale display there are several issues that need to be addressed to facilitate the interaction. In the thesis, three main topics for collaborative visualization are discussed; display setup, interactive visualization, and visual fatigue. The problems that the author is trying to address in this thesis are how multiple users can interact with a shared large-scale display depending on the display setups and how they can interact with the shared visualization in a way that doesn’t lead to visual fatigue.

The first user study (Chapter 3) explores the display setups for multi-user interaction with a shared large-display. The author describes the design of the three main display setups (a shared view, a split screen, and a split screen with navigation information) and a demonstration using these setups. The user study found that the split screen and the split screen with navigation information can improve users’ confidence and reduce frustration level and are more preferred than a shared view. However, a shared view can still provide effective interaction and collaboration and the display setups cannot have a large impact on usability and workload.

From the first study, the author employed a shared view for multi-user interactive visualization with a shared large-scale display due to the advantages of the shared view. To improve interactive visualization with a shared view for multiple users, the author designed and conducted the second user study (Chapter 4). A conventional interaction technique, the mean tracking method, was not effective for more than three users. In order to overcome the limitation of the current multi-user interactive visualization techniques, two interactive visualization techniques (the Object Shift Technique and Activity-based Weighted Mean Tracking method) were

developed and were evaluated in the second user study. The Object Shift Technique translates the virtual objects in the opposite direction of movement of the Point of View (PoV) and the Activity-based Weighted Mean Tracking method assigns the higher weight to active users in comparison with stationary users to determine the location of the PoV. The results of the user study showed that these techniques can support collaboration, improve interactivity, and provide similar visual discomfort compared to the conventional method.

The third study (Chapter 5) describes how to reduce visual fatigue for 3D stereoscopic visualization with a single point of view (PoV). When multiple users interact with 3D stereoscopic VR using multi-user interactive visualization techniques and they are close to the virtual objects, they can perceive 3D visual fatigue from the large disparity. To reduce the 3D visual fatigue, an Adaptive Interpupillary Distance (Adaptive IPD) adjustment technique was developed. To evaluate the Adaptive IPD method, the author compared to traditional 3D stereoscopic and the monoscopic visualization techniques. Through the user experiments, the author was able to confirm that the proposed method can reduce visual discomfort, yet maintain compelling depth perception as the result provided the most preferable 3D stereoscopic visualization experience.

For these studies, the author developed a software framework and designed a set of experiments (Chapter 6). The framework architecture that contains the three main ideas are described. A demonstration application for multi-dimensional decision making was developed using the framework.

The primary contributions of this thesis include a literature review of multi-user interaction with a shared large-scale display, deeper insights into three display setups for multi-user interaction, development of the Object Shift Techniques, the Activity-based Weighted Mean Tracking method, and the Adaptive Interpupillary Distance Adjustment technique, the evaluation of the three novel interaction techniques, development of a framework for supporting a multi-user interaction with a shared large-scale display and its application to multi-dimensional decision making VR system.

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Chapter 5 / Page 109-125

1. Kim, H., Lee, G., & Billinghurst, M. (2015, March). Adaptive Interpupillary Distance Adjustment for Stereoscopic 3D Visualization. In *Proceedings of the 14th Annual ACM SIGCHI_NZ conference on Computer-Human Interaction* (p. 2). ACM.

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Name: *Gun Lee* Signature: Date: *20/04/2017*

Publications from this dissertation

Material from this dissertation has been previously published or submitted in the peer-reviewed papers, posters, and extended abstracts listed below. The chapters of this thesis that relate to each publication are noted.

1. Kim, H., Lee, G., & Billinghurst, M. (2015, March). Adaptive Interpupillary Distance Adjustment for Stereoscopic 3D Visualization. In *Proceedings of the 14th Annual ACM SIGCHI_NZ conference on Computer-Human Interaction* (p. 2). ACM. Described in the Chapter 5.
2. Kim, H., Kim, Y., Lee, G., Billinghurst, M., & Christoph, B. (04/30/2017 submitted). Improving multi-user interactive visualization with a shared-large scale display. *Computers & Graphics*, Described in the Chapter 4.

During my doctoral studies, the following papers were also published, but are not a part of this thesis.

1. Kim, H., Lee, G., & Billinghurst, M. (2015, December). A Non-linear Mapping Technique for Bare-hand Interaction in Large Virtual Environments. In *Proceedings of the Annual Meeting of the Australian Special Interest Group for Computer Human Interaction* (pp. 53-61). ACM.
2. Piumsomboon, T., Altimira, D., Kim, H., Clark, A., Lee, G., & Billinghurst, M. (2014, September). Grasp-Shell vs gesture-speech: A comparison of direct and indirect natural interaction techniques in augmented reality. In *Mixed and Augmented Reality (ISMAR), 2014 IEEE International Symposium on* (pp. 73-82). IEEE.
3. Nassani, A., Kim, H., Lee, G., Billinghurst, M., Langlotz, T., & Lindeman, R. W. (2016, November). Augmented reality annotation for social video sharing. In *SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications* (p. 9). ACM.

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Lastly, I would like to dedicate this work to my parents, who always believed in me. This would not have been possible without your unwavering support.

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Abbreviations

AWMT	Activity-based Weighted Mean Tracking
FPS	Frame Per Second
HMD	Head Mounted Display
IPD	Inter Pupillary Distance
MDG	Multi Display Groupware
MT	Mean Tracking
NI	Navigation Information
OST	Object Shift Techniques
PoV	Point of View
SDG	Single Display Groupware
SUS	System Usability Scale
VE	Virtual Environment
VR	Virtual Reality

Chapter 1

Introduction

This dissertation explores how multiple users interact with an immersive virtual reality visualization on a shared large-scale display and how to improve the multi-user interactive visualization.

1.1 Background

The first concept of Virtual Reality (VR) was a goggle-based "*Pygmfalion's Spectacle*" from a science fiction story written in 1935, which included holographic imagery, smell, and touch (Weinbaum 1935). In 1962, Morton Heilig built the "*Sensorama*", the first mechanical multi-sensory stereoscopic system engaging vision, sound, smell, and haptic[1]. In half century since these early concepts and prototypes, VR systems have developed in various ways. With the advance of display hardware and computer graphics technology, VR can now provide a very realistic virtual environment (VE). The high quality of auditory, olfactory, gustatory and haptic hardware and techniques additionally increase realism and immersion in VE. Early VR technology was focused on specialized and professional applications such as flight simulation (Jones 1999) or medical training (Ziv 2003; Kunkler 2006), but now VR is becoming more available to members of the public through inexpensive desktop and mobile VR solutions. VR is now

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[1] "Sensorama simulator." U.S. Patent 3,050,870, issued August 28, 1962.

also available in a wide variety of domains such as cinemas[2], games[3], advertisement[4], amusement parks[5], and even museums[6].

There are different types of display hardware that can be used in a VR system. In terms of display hardware for individual users, Head-Mounted Displays (HMD) have recently become popular as consumer grade computers can display high-quality graphics, and the price of HMD component hardware has become cheaper. With the introduction of the Oculus[7] and the HTC VIVE[8], HMD technology is available at an affordable price to consumers. Although an HMD provides an individual immersive VR experience, they may cause discomfort, and the user cannot see his/her real body which may limit the user's level of presence in the VE (Cakmakci 2006). Another VE display technique is to use a large-screen or projected imagery. This setup can also provide an immersive VR experience and in addition can also easily support multiple users. However, this setup may require a large space and multiple displays to cover the space depending on the hardware setup.

Multi-user visualization and interaction techniques are becoming more popular as the number of people using VR increases. To support multiple users, two options are to use several HMDs, or a large-scale wall display (Cordil 2017) (see Figure 1.1.1). Several literature reviews describe the

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[2] VR cinema, https://thevrcinema.com/
[3] VR games, http://store.steampowered.com/steamvr
[4] VR advertisement, https://virtualsky.com/
[5] VR amusement, https://thevoid.com/
[6] VR museum, https://www.fi.edu/vr-at-the-museum
[7] Oculus, https://www.oculus.com
[8] HTC VIVE, https://www.vive.com

positive and negative aspects of each approach (Urey 2011; Holliman 2011).

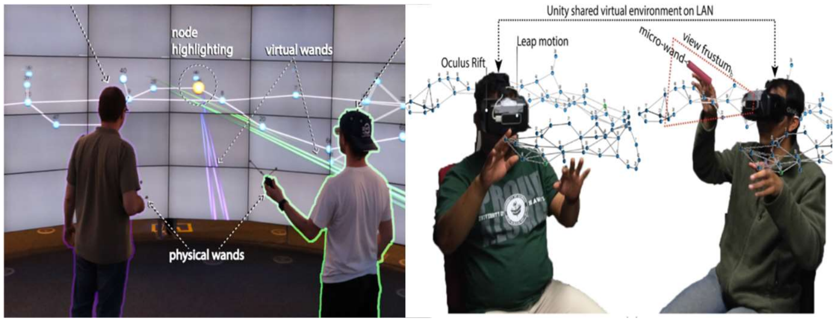

Figure 1.1.1. A large-scale wall display(left) and multiple HMD hardware setup (right) (Cordeil 2017).

Providing an individual HMD for each user is a simple way to implement multi-user interaction. Using multiple HMDs can provide an individual personal view to each user although this may increase the cost depending on the number of users and the sense of co-presence could be limited because the users cannot see each other in the VE (Cakmakci 2006). This problem could be solved by showing virtual avatars, but these are at a lower visual fidelity compared to physically seeing each other in the real world. Several researchers have attempted to show a realistic body of the user in a virtual environment using a camera (Bruder 2009; Gunther 2015). Such an approach can help a person to see him/herself in the virtual environment, however, the systems cannot provide views of other users (especially their faces) and are limited to showing only part of the body, such as a hand (see Figure 1.1.2).

Figure 1.1.2. Augmented a real body into virtual space. (Bruder 2009)

Compared to the multiple HMDs setup, a single shared large-scale display can provide an immersive VE as well as co-location and co-presence cues as the display enables users to share the same physical space. In this thesis, the author employed the single shared large-scale display rather than using multiple HMDs for collaborative interaction. With a single shared large-scale display, users can understand other users' emotion better by reading their face and body gestures. This can help collaboration and discussion between users.

For a single shared large-scale display, a common display setup for multiple users is to share a large-scale display with a single visualization view that all user's share. This technique is cost-effective because it does not need special hardware. However, the technique usually employs a single point of view (PoV) for the visualization and may not provide a proper view for each user if they are standing in very different places in front of the display. This single PoV may cause visual sickness if 3D stereoscopy is provided and the users' viewpoints and the single PoV are not aligned together. Also, there can be control issues if each user tries to have individual control over the display viewpoint. Another display setup is a split screen, which splits a large-scale display and each screen can be used by the single user. This setup can provide independent screens for users and can increase users' presence. Also, it supports to share visualization and information. However, the number of split screens can be limited due to the screen space.

Displaying different views for individual users on a single large screen is possible through the use of special hardware (Blom 2002; Agrawala 1997; Arthur 1998), and is called a multi-view display. There are a number of technologies that are capable of supporting multi-view displays including lenticular displays (Takaki 2010), parallax-barrier or masked displays (Lee 2006), and shutter displays (Brosnihan 2010). These technologies help support multi-user interaction with individual views and increase co-presence of the users. However, the number of users may be limited due to the hardware limitation and there may be problems with lower resolution, lower brightness, and increased hardware cost (Holliman 2011). Providing individual views also does not guarantee better collaboration and sharing of information. The transition between individual and collaborative activities for the shared information and methods for supporting mutual awareness of other's activities must be designed explicitly (McGill 2015).

In spite of the disadvantages of a shared large-scale display, they have been widely used for multi-user interaction because users can collaborate in the same space and discuss the same visualization. Although many techniques have been developed for multi-user interaction with a shared large-scale display, there is still a lack of effective interaction techniques and many topics that have not been explored yet. Therefore, it is important to research multi-user interactive visualization with a shared large-scale display.

This dissertation explores how multiple people can interact with immersive visualization with a shared large-scale display effectively with less visual fatigue. The remainder of this chapter describes research questions, research approach, a main experimental system, contribution of the thesis, and an overview of the Ph.D. work (thesis structure).

1.2 Problem statement

This thesis is focused on exploring multi-user interaction with an immersive visualization system using a shared large-scale display. When the multiple users interact with a virtual environment on a large-scale display, there are several issues that need to be addressed to facilitate the interaction. In the thesis, three main topics for collaborative visualization are discussed; display setup, interactive visualization, and visual fatigue. The problems that the author is trying to address in this thesis are how multiple users can interact with a shared large-scale display depending on the display setups and how they can interact with the shared visualization in a way that doesn't lead to visual fatigue. A display setup for multiple users is an important problem because this can have an impact on the interaction performance, usability, and workload. Secondly, multiple users can have difficulties in interacting with visualization and can perceive visual fatigue more if a collaborative visualization system cannot provide proper interactive visualization for multiple users. Thirdly, collaborative visualization has to provide a visually comfortable environment with less visual fatigue to let users interact with visualization effectively.

Traditionally, visualization systems are designed for a single user on a desktop computer and collaborative visualization (or multi-user visualization) systems have extended the traditional concept of visualization in order to support multiple users. Collaborative visualization also incorporates research from other fields such as distributed computing, human-computer interaction, and computer-supported cooperative work (CSCW) (Isenberg 2011). While collaborative visualization benefits from work in these disciplines, there are many challenges, aspects, and issues that are unique to the intersection of collaborative work and visualization. These include human-centered interactive visualization, fatigue for multi-user interaction, and coordinating user input in collaborative visualization systems.

Previously, several definitions of collaborative visualization have been given (Pea 1993; Raje 1998; Li 2006), but these were typically a general definition for visualization as the use of computer-supported, interactive, visual representations of information to amplify cognition (Card 1999). Recently Isenberg et al. (2011) redefined it to describe the entire scope that collaborative visualization can encompass;

> C*ollaborative visualization is the shared use of computer-supported, (interactive,) visual representations of data by more than one person with the common goal of contribution to*

joint information processing activities.

There are many ways to categorize collaborative visualization, however, the space-time matrix is often broadly used (see Figure 1.2.1). This classifies collaborative systems according to where they occur in space (distributed or co-located) and in time (synchronous or asynchronous). Collaborative visualization systems can cross the boundaries of this matrix. For instance, both synchronous or asynchronous collaboration can be supported by the same system. Figure 1.2.1 depicts examples of the collaborative visualization categorized by space-time matrix.

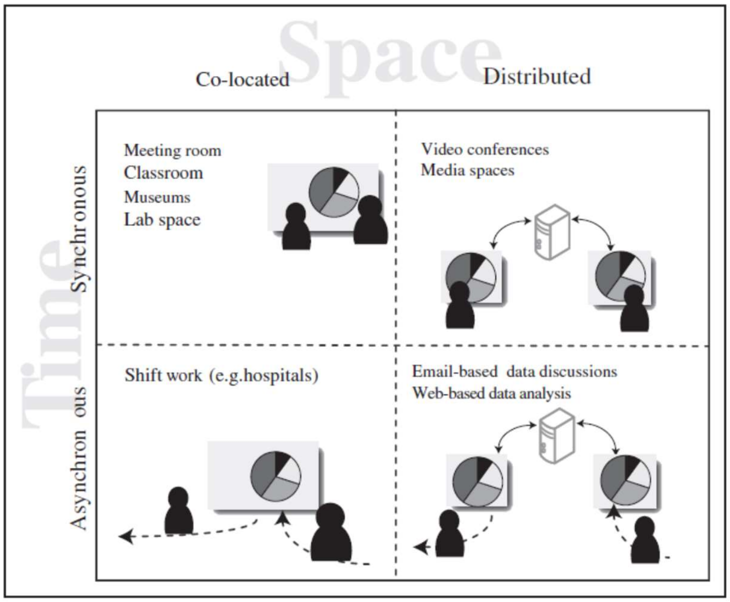

Figure 1.2.1 Examples of collaborative visualization categorized by space-time matrix (Baecker 1993; Dix 1998)

In distributed collaborative visualization, one of the challenging topics was efficient architectures and synchronization techniques to communicate remote work with large datasets (Ang 1995; Wood 1997; Li 2006; Renambot 2009). For this, the communication over the web (Ang 1995), grid computing (Jankun-Kelly 2003; Koyamada 2004) and special hardware environment such as CAVEs (Leigh 1999) were considered. Recently, the research focus has moved from technical aspects such as network latency, synchronization, and framerate to social and human-centered questions such as how to engage a number of audiences in discussing and exploring information or how non-experts can share data and visualization effectively on online (Heer 2008).

For co-located collaborative visualization, systems can be categorized into Single Display Groupware (SDG) and Multi Display Groupware (MDG) (Stewart 1999). Examples of SDG are large interactive walls (Guimbretière 2001) or table-top displays (Wellner 1993). Some of the main research topics in SDG are coordination of activities in the workspace (Morris 2004; Scott 2004; Nacenta 2007), awareness of member's activities (Tang 2006), and access and transfer in/between workspace(s) (Kruger 2004). Multi-touch technology enables users to interact with the system independently and synchronously, but, these synchronous inputs lead to new challenges. Research has been conducted to address methods for coordinating user input in collaborative visualization systems (Forlines 2005; Isenberg 2007; Heer 2008; Isenberg 2009; Tobiasz 2009).

Examples of MDG are distributed multiple displays and a single display with multiple individual devices. Research on MDG has included exploring coordinating input and output from multiple different display devices such as a large display with mobile devices (Johanson 2002). Previous research addressed molecular visualization across large displays and a table-top (Forlines 2008), geospatial visualization across a similar display (Forlines 2006), and multiple display setups using a network communication to share visualizations from laptops on large displays (Wigdor 2009).

In co-located collaborative visualization, there are a lot of the research topics such as how to design display interfaces and control interfaces (Morris 2004; Kruger 2004; Scott 2004; Nacenta 2007; Isenberg 2009), how to design a virtual environment for a specific purpose (Tollinger 2004; Huang 2006), how to leverage visualization techniques in scientific fields (Kilman 1997; Schissel 2004; Bernholdt 2005), and how to improve social interaction (Isenberg 2011; Cogburn 2003). However, there haven't been much study on how to design display interfaces, how to improve interactive visualization and how to reduce 3D visual fatigue, that this thesis mainly focuses on.

Many visualization applications have been developed and for table-top interfaces (Vernier 2002; Shen 2003; Tse 2007; Forlines 2008; Lissermann 2014), and wall-size displays (Stefik 1987; Streitz 1999; Johanson 2002; Izadi 2003; Prante 2004; Wigdor 2009) to support seamless, effective and natural multi-user interaction. They mostly employed a shared view that enables users to access the whole space on the screen together. Several studies (Tse 2007; Lissermann 2014; McGill 2015) evaluated their interfaces by comparing a shared view and a split screen. In a few studies in the television industry (McGill 2014), several advantages and disadvantages of a shared view and a split screen display setup for multi-user interaction were briefly discussed, but they were not explored in detail. McGill et al (2015) also evaluated display setups for multiple users, but they did not provide equitable control interfaces to evaluate their visual interfaces. Therefore, it is necessary to evaluate display setups for multi-user visualization with a shared large-scale display in order to investigate the effect of display setup and the relationship between display setups and multi-user interaction.

Another issue in collaborative visualization is improving interactivity for multiple users. In a typical multi-user interaction scenario with a shared display, only one user, the "leader", can interact with the virtual environment using an input device, while the other viewers, the "followers", only see the scene from the leader's viewpoint. In this scenario, a leader needs to hand over the input device to another person if they want to transfer of viewpoint control. The followers may feel uncomfortable or even have nausea if their views in the real world are significantly different from the leader. Visual fatigue can become worse in collaborative visualizations with 3D stereoscopy. An alternative is tracking multiple users instead of tracking a single user (the leader). This approach often employs a Mean Tracking method that averages the locations of all the users to determine the location of a single point of view (PoV). This is a common tracking method for multi-user visualization (Marbach, 2009; Schulze 2012; Tripicchio 2014), and can reduce visual sickness for users, but it is not able to efficiently reflect individual users' movement. Users can be frustrated when they move because the PoV moves slowly as the system averages the movements of all users sharing a screen. Therefore, the Mean Tracking method is not an optimal solution for interactive collaboration visualization and it is necessary to enhance interactive collaborative visualization.

When designing interactive visualization for multiple users, 3D visual fatigue can be another problem. There are several causes of the visual fatigue in 3D stereoscopic visualization such as crosstalk, depth of field, motion, inappropriate disparity, and cardboard effect. Inappropriate disparity is one of the major causes of 3D visual fatigue and many techniques have been developed to reduce this. The approaches to reduce visual discomfort from inappropriate disparity can be categorized into depth (disparity) remapping techniques (Konrad 1999; Kishi 2008; Ide 2010; Holliman. 2004; Lang 2010; Wu 2011; Sohn 2014; Oh 2015), generating empty depth information (Park 2004), and adjusting camera separation (Mangiate 2012). These techniques can increase visual comfort although they have several limitations such as computation complexity. Therefore, another approach is required to reduce visual discomfort for multi-user interactive visualization.

This thesis has a number of novel contributions compared to previous research as following:

1. Investigated of deeper insights of the display setups for multiple users.

2. Proposed the novel interactive visualization techniques for multiple users with a shared large-scale display in order to provide effective interaction and visualization.
3. Proposed the 3D visual fatigue reduction technique for 3D multi-user interactive visualization.
4. Developed the multi-user interactive visualization framework to facilitate building a multi-user virtual environment.

1.3 Research Aim

The dissertation investigates display setups for multiple users with a shared large-scale display and explores how to improve interactive visualization for multiple users and how to reduce the visual fatigue in 3D stereoscopy for collaborative visualization. The main aims of the thesis are to:

1. Understand the approaches and limitations of the technology of current multi-user interactive visualization with a shared large-scale display (Chapter 2).
2. Understand the display setups for multi-user visualization with a shared large-scale display and relevant display interfaces (Chapter 3).
3. Learn the effects of the display setups and the relationship between display setups and multi-user interaction (Chapter 3).
4. Understand the current interactive visualization techniques for multiple users with a shared large-scale display and limitations of them (Chapter 2 and Chapter 4).
5. Propose how to improve multi-user interactive visualization with a shared large-scale display and evaluate them (Chapter 4).

6. Understand the causes of the visual fatigue from 3D stereoscopy and limitations of the techniques to reduce 3D visual fatigue (Chapter 2 and Chapter 5).
7. Learn the relation between interpupillary distance and visual fatigue (Chapter 5).
8. Suggest how to increase visual comfort when multiple users interact with a shared large-scale display and evaluate them (Chapter 5).
9. Develop a multi-user interactive visualization framework to utilize the ideas from the user studies (Chapter 6).

1.4 Research Approach

This section addresses the research approach, the relationship between the studies.

This research starts with exploring how to improve 3D interactive visualization with a shared large-scale display for multiple users. The first main user study in Chapter 3 was designed to investigate display setups with a shared large-scale display for multiple users. The second study in Chapter 4 was about how to improve interactive visualization when many users interact with a shared large-scale display. In the third study in Chapter 5, a technique for reducing visual fatigue in an interactive visualization system was discussed. For these studies, the author developed an underlying software framework (Chapter 6) and designed a set of experiments.

The research starts with a literature review on 3D multi-user interactive visualizations with a shared large-scale display. This review contains the display setups for a shared large-scale display, and an overview of interactive visualization techniques including supporting individual views such as a multi-view display as well as main factors that cause visual fatigue in 3D stereoscopy.

From the literature review, the author doubted which display setups are effective for multi-user visualization and how the display setups can influence the multi-user interaction. To investigate the effect of display setups and the relation between display setups and multi-user interaction, the author conducted a user study to evaluate the common display setups for multiple users (a shared view, a split screen, and a split screen with navigation information). From the results of the experiment, the author made several insights into the design of a display setup for multiple users.

From the first study, the author employed a shared view for multi-user interactive visualization with a shared large-scale display due to the advantages of the shared view. The split screen and the split screen with navigation information can improve users' confidence and reduce frustration level and are more preferred than a shared view. However, a shared view can still provide effective interaction and collaboration and the display setups cannot have a large impact on usability and workload. Therefore, a shared view was employed in the thesis research because the exploration and discussion in a virtual environment require more information and space to display.

To improve interactive visualization with a shared view for multiple users, the author designed and conducted the second user study. A pilot study using a conventional interaction technique, the mean tracking method, with three users showed that this was not effective. Therefore, two interactive visualization techniques were developed for multi-user interaction and were evaluated in the second user study. These techniques can support collaboration, improve interactivity, and provide similar visual discomfort compared to the conventional method.

While using interactive visualization, users still felt visual fatigue. When multiple users interact with 3D stereoscopic VR using multi-user interactive visualization techniques and they are close to the virtual objects, they can perceive 3D visual fatigue from the large disparity. So, the author introduced a 3D visual fatigue reduction technique for 3D stereoscopy. Multi-user interaction with a shared view uses a single point of view (PoV) to visualize on the screen, so the author simulated visualization with a single PoV and tested it with a single user. From the findings of the evaluation, the author suggested a 3D visual fatigue reduction technique for multi-user interactive visualization systems.

For these studies, the author developed a software framework described in Chapter 6 and designed a set of experiments. Chapter 6 describes the framework architecture that contains the three main ideas. A demonstration application for multi-dimensional decision making was developed using the framework.

1.5 Experimental System

To study the 3D multi-user interactive visualization with a shared large-scale display, the author used a three-sided projection based immersive visualization display (2.8m by 1.8m for each screen) (see Figure 1.4.1), named "*VisionSpace*". The system provides immersive virtual environment for multiple users with a multi-user tracking system. The whole display has resolution of 3072 by 768 pixels. The three screens were aligned at an angle of 120 degrees so that they formed a shape of a half of a hexagon from the top down view. For 3D stereoscopic visualization, the system uses passive circular polarization filters on the projectors and on the glasses. A set of reflective balls attached to glasses is tracked by an ART tracking camera system (ART)[9] to obtain the position and rotation of the two participants. The

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[9] ART tracking system, http://www.ar-tracking.com/

interactive visualization was run on the computer with an Intel Quad-core Q9550 2.83GHz with triple SLI Nvidia GTX 260 graphics cards. Samsung Nexus 10[10] tablets were used as control devices and a mobile user interface was built for them with the Unity 3D [11] graphics engine. The OpenSceneGraph [12] library and the Virtual Reality Peripheral Network (VRPN) [13] library were used to render the data visualization and to communicate with the ART tracking system, respectively. The visualization system communicated with the tablets using the Window Socket protocol[14]. Details of each interface design used in the studies are addressed in the corresponding chapters of each user study.

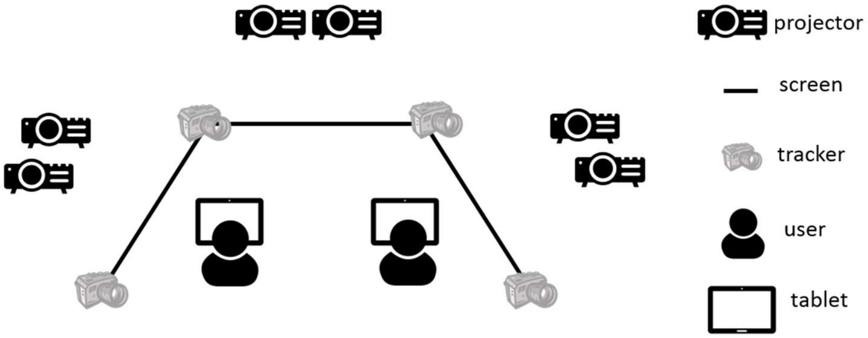

Figure 1.4.1 Top down view of the experiment setup.

1.6 Research Contributions

This thesis makes a number of contributions to research in multi-user interaction with a shared large-scale immersive display.

1. A literature review of multi-user interaction with a shared large-scale

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[10] Samsung Nexus 10 (http://www.samsung.com/us/support/owners/product/google-nexus-10-tab-wi-fi)
[11] Unity3D (https://www.unity3d.com/)
[12] Open Scene Graph (https://www.openscenegraph.org)
[13] Virtual Reality Peripheral Network (https://github.com/vrpn/vrpn)
[14] WinSock (https://msdn.microsoft.com/en-us/library/windows/desktop/ms737523(v=vs.85).aspx)

display and relevant areas. The review focused on display setups, interactive visualization, and 3D visual fatigue for multiple users.

2. Deeper insights into three display setups for multi-user interaction with a shared large-scale display.
3. Development of two novel multi-user interactive visualization techniques (the Object Shift Techniques and the Activity-based Weighted Mean Tracking method) that support interaction with multiple users and help to reduce the visual fatigue.
4. Development of an Adaptive Interpupillary Distance Adjustment technique that can reduce visual fatigue caused by the extreme disparity between the views of the users' left and right eyes.
5. Demonstration and user evaluation of three display setups (a shared view, a split screen, and a split screen with navigation information). The user study includes the evaluation of interaction performance, collaborative usability, and user preference.
6. Implementation and evaluation of the three novel interaction techniques (the Object Shift Techniques, the Activity-based Weighted Mean Tracking method, and the Adaptive Interpupillary Distance Adjustment technique). Each user study measured interaction performance, depth perception, visual fatigue, usability, and performance.
7. Development of a framework for supporting a multi-user interaction with a shared large-scale display and its application to multi-dimensional decision making VR system. The framework not only supports the novel interaction techniques mentioned above but also includes fundamental multi-user interaction functions such as head tracking, network synchronization, and 3D visualization.

1.7 Thesis Structure

This thesis aims to understand multi-user interactive visualization with a shared large-scale display and to improve the user experience. Based on these goals, the rest of this thesis includes chapters on investigating display setups for a shared large-scale display, improving multi-user interactive visualization, and reducing 3D visual fatigue.

In Chapter 2, the state art of 3D multi-user interactive visualization with a shared large-scale display is introduced. Firstly, the review of the display setups for multi-user interaction is explored, then an overview of interactive visualization for multiple users is given, and the main limitations of conventional multi-user visualization is discussed. Lastly, the main causes of visual fatigue with 3D stereoscopy are explored and the problem of large disparity is mainly discussed.

Chapter 3 investigates the display setups for multi-user interaction with a shared large-display. The author describes the design of the three main display setups and a demonstration using these setups. Using these display setups, a user study was conducted and its results are discussed.

In Chapter 4, interactive visualization techniques for multiple users are discussed. In order to overcome the limitation of the current multi-user interactive visualization techniques, two new interaction techniques are discussed and a detailed implementation of the techniques are described. A user study to evaluate the interaction techniques is presented and the results of the user study and further comments are discussed.

Chapter 5 describes how to reduce visual fatigue for 3D stereoscopic visualization with a single point of view (PoV). To reduce the 3D visual fatigue, an adaptive interpupillary distance (Adaptive IPD) adjustment technique was developed. The first user study for measuring the proper IPD is described and then based on the result of this first study, the second user study was conducted to evaluate the adaptive IPD method compared to traditional 3D stereoscopic and the monoscopic visualization techniques.

In Chapter 6, a framework for 3D multi-user interactive visualization and a prototype application for multi-dimensional decision making are covered. Firstly, the architecture and main features of the framework are described in detail. Secondly, the definition and the terminology of a multi-dimensional decision making are briefly introduced, then a detailed implementation of the application is discussed, using the framework the author has developed.

Chapter 7 contains a discussion of the thesis. This includes a summary of the thesis, an overview of the research progress, and a description of the limitations of the research. This thesis concludes in Chapter 8 with a presentation of directions for future work.

Chapter 2

Related Work

This chapter describes relevant prior research in 3D multi-user interactive visualization with a shared large-scale display. First, previous research is discussed on display setups for multiple users with a shared large-scale display including related display interfaces. Secondly, previous works on interactive visualization with a shared large-scale display for multi-user interaction are explored. Thirdly, the causes of the visual fatigue from the 3D stereoscopy and previous works to reduce the fatigue are described.

2.1 Display Setups for Multiple Users

This section describes the fundamental categories for display setups (Single Display Groupware and Multi-Display Groupware) for multi-user interaction including their advantages and disadvantages. Next, the related work including other similar research to the thesis is explored.

2.1.1 Single Display Groupware and Multi-Display Groupware

For a shared large-scale display for multiple users, there are two main display configurations. One is Single Display Groupware (SDG) and another is Multi-Display Groupware (MDG) (Stewart, 1999; McGill 2015). In SDG, users share a single display in order to provide a collaborative environment for activities like face to face discussion. SDG enables users to share their attention (Gross 2013) and increases users' ability to collaborate (Wallace 2009). The display setup improves the collaborative experience although it restricts users' independency. In MDG, multiple users use additional displays such as personal private screens or multiple shared screens in order to provide private and independent environments or distributed display environments.

The MDG allows users to have task independence and selective or casual awareness (McGill 2015) and can provide a collaborative environment. However, the MDG can disperse users' attention due to having multiple displays and it may not be cost-effective because it requires multiple display hardware. In this thesis, SDG is mostly discussed for multi-user interaction because it can be better for providing collaborative environments for multiple users. Figure 2.1.1 shows an example of SDG and MDG.

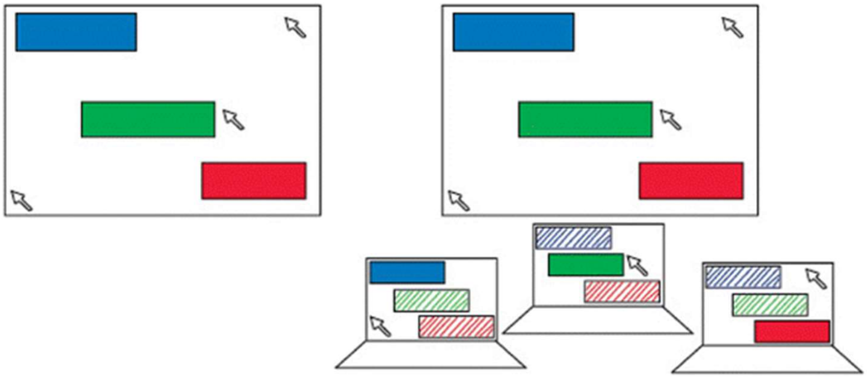

Figure 2.1.1 An example of Single Display Groupware (left) and Multi-Display Groupware (right) (Wallace 2009)

MDG usually employs multiple display hardware to provide multi-user interaction, such as multiple shared displays or multiple shared displays with multiple individual displays. Previous research on MDG has shown the advantages and the possibilities of different hardware combinations (Stefik 1987; Johanson 2002; Izadi 2003; Everitt 2006; Lissermann 2014). Compared to MDG, research on SDG that uses a single large display for multi-user interaction is relatively scarce. Most studies on SDG have focused on table-top display interfaces since touch and gesture interaction can solve control issues, such as how to use/share a controller and how to switch between sharing space and use of individual space. In next section, the related work in table-top display interfaces and other similar research to the thesis will be discussed.

2.1.2 Co-located Collaboration Display Interfaces

The responsive workbench was one of the earliest visualization systems for co-located collaboration around a large horizontal surface (Kruger 1995). It provided a virtual reality environment that displayed shared 3D scenes via shutter glasses to people standing around the table. Several scientific visualization applications such as fluid simulation and situational awareness applications were developed on the platform as shown in Figure 2.1.2. (Wesche 1999).

Figure 2.1.2 Fluid simulation on the responsive workbench (Wesche 1999)

Vernier et al. (2002) developed a multi-user round interactive table-top display based on radial tree layouts and two different fisheye interfaces to support multi-user collaborative works. The system facilitated user interaction for relocation, reorientation, scaling and layout on a circular table. Figure 2.1.3 illustrates the circular table interface and visual representations on the table.

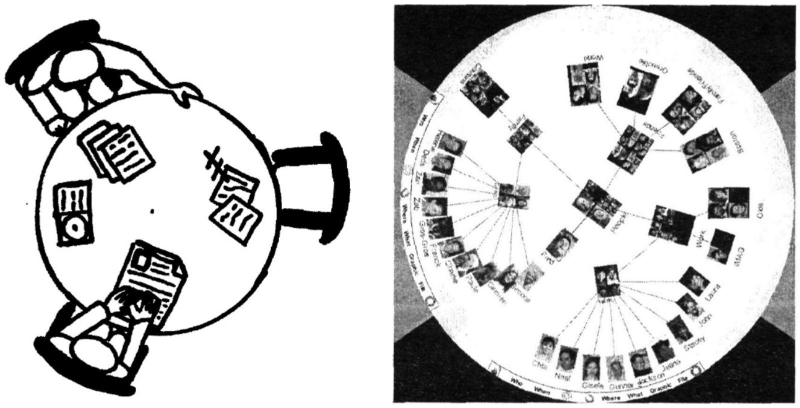

Figure 2.1.3. Circular table interface (left) and radial tree representation (right) (Vernier 2002)

Tse et al. (2007) explored a multimodal independent display, shared display, and True groupware display (remote display) on a table-top interface and offered a generalized approach for each setup. The independent display setup provides separable interaction, the shared display supports rich awareness for each user, and the True groupware display allows remote users to work in parallel on a large screen. Figure 2.1.4 shows the different display setups.

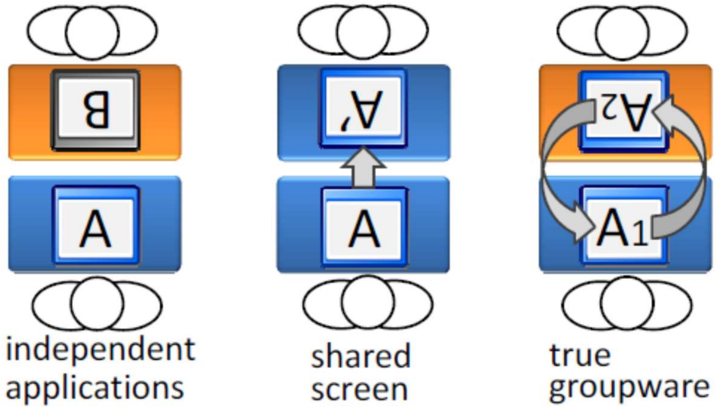

Figure 2.1.4. Independent display (left), shared display (center), and True groupware display (right) on the table-top interface (Tse 2007).

Recently, Permulin integrated a set of interaction and visualization techniques for multiple users using a table-top display and a shutter display to support co-located collaboration (Lissermann 2014). This system provided not only private views but also a shared view, and additional gesture interaction allowed users to independently control each view. They evaluated the prototype system by comparing it to a conventional table-top setup and a split screen configuration. From the evaluation, they found that the Permulin setup enables users to share information as well as to support private work unobtrusively. However, the system is basically a multi-view system, which may not be optimal for collaboration with a large-scale display in terms of sharing information. Figure 2.1.5 shows the overall hardware setup and system concept.

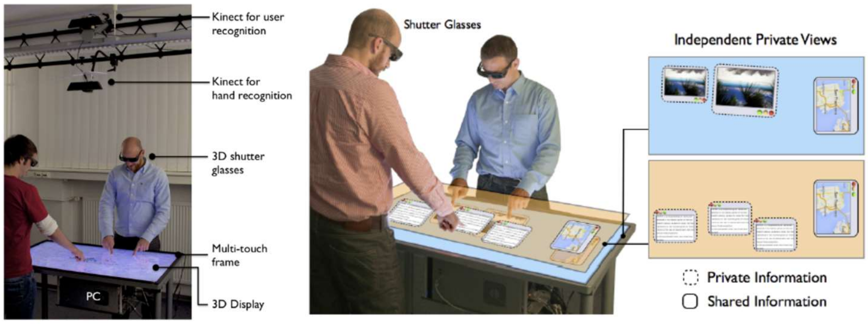

Figure 2.1.5 Permulin hardware setup (left) and system concept (right) (Lissermann 2014)

Compared to the table top display for collaboration, several wall-display techniques have also been developed. The *Collab* system was one of the first to provide a collaborative environment for people to work together face to face or remotely on multiple desktops and a large display wall (Stefik 1987). *Dynamo* supported the ability to transfer users' media to a shared display (Izadi 2003). Digital furniture and interaction techniques were designed to support spontaneous collaboration using the *InteractTable, Dyna Wall,* and *CommChairs* interfaces (Streitz 1999; Prante 2004). Using these systems users could interconnect laptops and furniture components to construct ad hoc collaborative spaces. *UbiTable* developed by Shen et al. (2003) provided spontaneous, walk-up-and-use functionality to share data, such as photos and notes. Everitt et al. (2006) designed interaction and document transfer techniques between vertical displays, a table, and portable devices. *iRoom* was designed to provide a seamless interactive environment (Johanson 2002). *WeSpace* was a collaborative workspace that integrated a large data wall with a multi-user multi-touch table for small groups for data exploration and visualization (Wigdor 2009). These interfaces could improve collaborative interaction using various hardware. In their studies and development, they employed a single shared view and the research mainly focused on the development of user interfaces and interaction between interfaces and users or between interfaces.

Rogers and Lindley made several observations from user studies comparing vertical and horizontal interactive displays in a city tour planning task (Rogers 2004). Users with the table display were more encouraged to switch roles, explore ideas and follow closely what each user was doing. In contrast, users found that a wall display is socially awkward for collaboration. Tan et al. (2006) showed that large displays can improve productivity in spatial tasks, and Ball and North (2005) showed the potential performance benefits of large displays in low-level navigation and visualization tasks. Hou et al. (2012) found that the larger displays are suitable for increasing immersion. They discovered that large displays increase the sense of self-presence than smaller displays and a user sacrifices many benefits of larger displays to indulge in using a personal device. They suggested that if possible the shared utilization of the screen would be preferable than the use of personal devices.

2.1.3 Research on other relevant topics.

There are several studies for display setups with a shared large-scale display.

The proxemic approach was suggested by Ballendat et al. (2010). The interaction technique was demonstrated with dynamic visualization on a shared view using proxemic information, location, and user view directions. The system varied the display setups such as the shared view and the multi-screen based on multiple users' behavior. Figure 2.1.6 depicts various display setups for multi-user interaction.

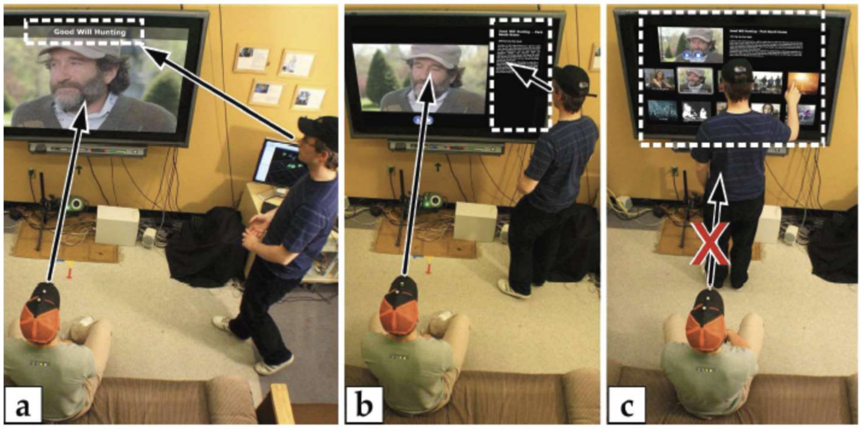

Figure 2.1.6 Examples of multi-user interaction using proximity. (Ballendat 2010)

Wallace et al. (2009) presented a user study to investigate differences between SDG and MDG as well as between interface configurations. Figure 2.1.7 shows the different experimental setups used. They used the Job Shop Scheduling task (Tan 2005) and three difference interface-access schemes (shared, negotiated (manual switch), and fixed access) to evaluate SDG and MDG systems. A single shared display was employed for SDG, and multiple personal displays with a single shared display were used for MDG. They showed that the MDG configuration provides advantages for performance for the individual task, while the SDG configuration offers advantages for coordinating access to shared resource. In SDG, the shared access scheme showed the best task completion time, task efficiency, low error rate compared to manual and fixed access schemes. However, the result of the solution optimality with the shared access scheme was lower than the other schemes.

Figure 2.1.7. MDG configuration(left) and SDG configuration (right) (Wallace 2009)

There was a user study that compares multi-view display with a shared view display and two individual displays (McGill 2015), as shown in Figure 2.1.8. To assess the advantages of a multi-view display, they conducted a user study with a loosely coupled task (independently searching for entertainment and deciding on one movie). They found that the multi-view display is preferable to the shared view display. They also revealed that the different awareness between multiple displays and the multi-view display exists because the multi-view display requires additional interaction to view partner activities. However, in the user study, a single controller was given to the users in the shared view condition and an individual controller was given for multiple displays and a multi-view display, which is an unfair comparison to evaluate each display setup in terms of a control interface. These different control interfaces may affect the results.

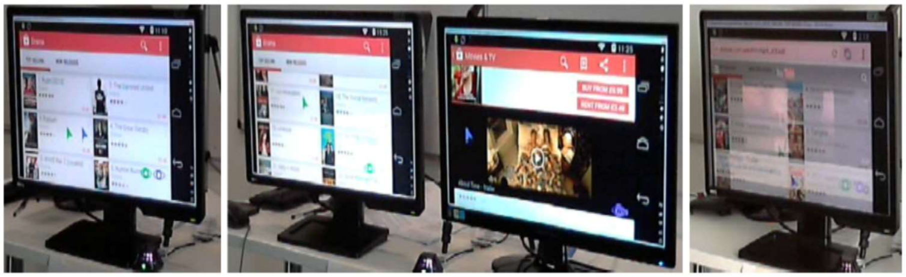

Figure 2.1.8. Single display with a shared controller (left), two displays with two controllers (center), and multi-view display with two controllers(right). (McGill 2015)

Although researchers have developed special purpose interaction components to mitigate the spatial interference in a shared SDG, the fact that the interference was not high in a shared SDG was found (Tse 2004). They studied how co-located people partitioned their collaborative drawing activities within a shared SDG environment. The result of the experiment revealed that people tend to avoid interfering with their partners by spatially separating their actions in the workspace.

2.2 Interactive Visualization for multiple users

This section explores interactive visualization techniques with a shared large-scale display for multiple users.

In multi-user interactive visualization with a shared large-scale display, several techniques can be used to support individual views such as visual filtering (Agrawala 1997), time multiplexing (Blom 2002), and physical separation technique (Arthur 1998). The visual filter technique (See Figure 2.2.1) displays two or four images on one physical screen and each user can see the images through filtered glasses. The user can share information, however, they can have a different individual view based on the position of the users. This technique usually requires many display sources to generate each view.

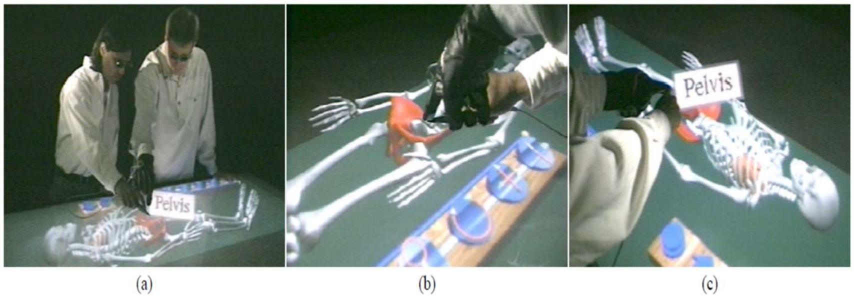

Figure 2.2.1. Multi-user interaction with visual filtering. Left and right users share the same information but have different views. (Agrawala 1997)

The time multiplexing technique displays the images for each eye and each user alternatively. Figure 2.2.2 illustrates the system configuration for time multiplexing technique. If the number of user increase, more images are required to be displayed, so that the system needs high-frequency refresh rate display to implement it.

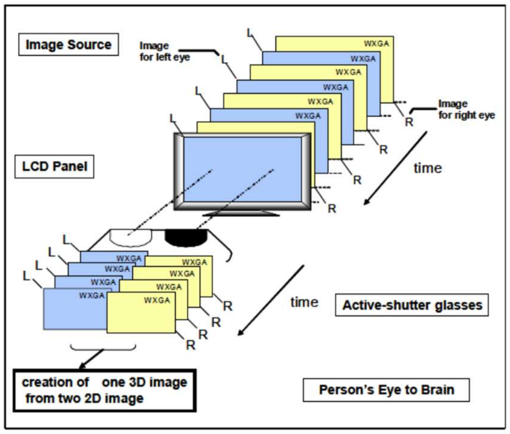

Figure 2.2.2. Time-sequential 3D system for one user. (Suzuki 2009)

The physical separation technique provides an individual screen for each user (See Figure 2.2.3). The system does not require a special display to support multiple users. The users can share the physical space as well as visualized information. However, the technique can restrict the number of users due to space limitation.

Figure 2.2.3. Physical separation for multiple users. Each user has his/her own physical screen but they share the visualization (Arthur 1998).

On the other hand, using a single shared viewpoint is another way to support multiple users, providing an identical view on a single display. This approach could be more cost effective than the individual view techniques mentioned. Early shared viewpoint techniques include the use of a common PoV (Blom 2002) and deformation of the projection method (Naemura 1998) to share viewpoints by distorting rendering scenes. Despite the advantages of using a shared viewpoint technique (i.e. low cost and easy implementation), it does not guarantee a correct perspective to all the users. However, the quality of the implemented visualization can be acceptable (Tripicchio 2014).

Simon et al. (2004) used spherical projection to generate an omnidirectional stereography (Omnistereo) used an object warping technique and a per-pixel-column technique that renders each pixel-column and merges them to create a scene, which is suited for non-tracked curved-screen virtual environments.

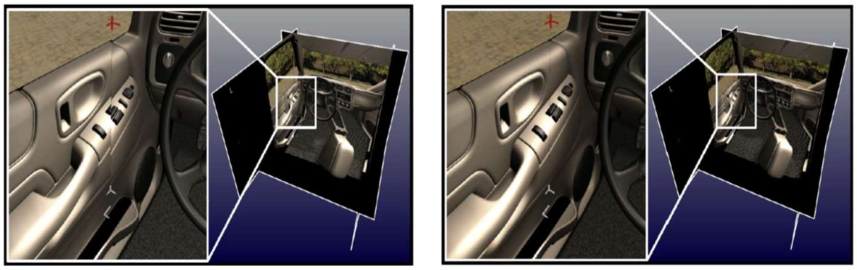

Figure 2.2.4. Breaks in the images due to screen edges (left) and no breaks with a per-pixel-column technique. (Simon 2004)

McGinity et al. (2007) built a cylindrical VR theater where up to 20 users could work together simultaneously using the Omnistereo technique. However, the Omnistereo does not use user-tracking hardware, so the capability of individual users to look around objects in the 3D world was limited.

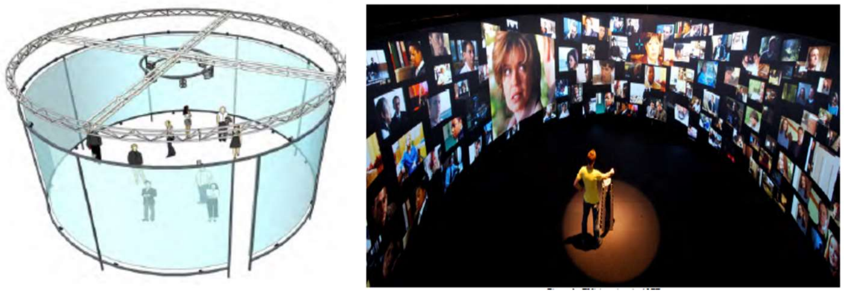

Figure 2.2.5. Hardware setup for AVIE (left) and an example application of the system (right) (McGinity 2007)

Image blending and view clustering techniques can support multiple users in a projected VE (Marbach 2009). Image blending renders independent views and composites the result into a final image when users look at the separate portion of the projection surface and blends images between independent images. In addition, when the users are looking at the same point, the system stops blending images and averages the users' viewpoints using a view clustering technique.

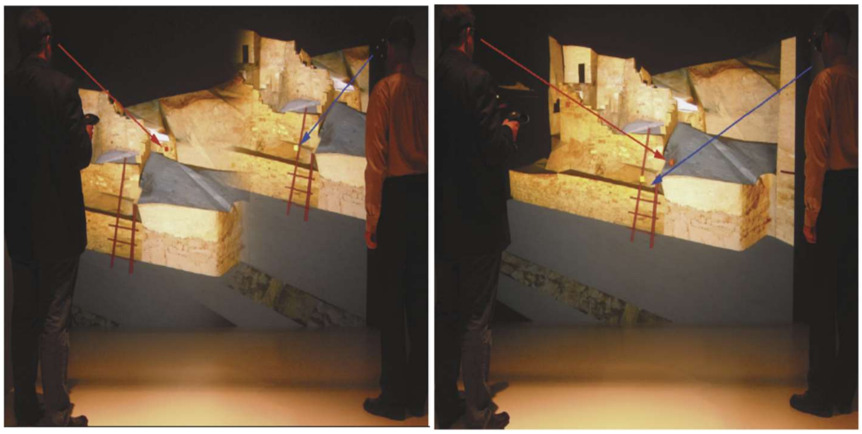

Figure 2.2.6. Image blending technique(left) and view clustering technique(right). (Marbach 2009)

Schulze et al. (2012) demonstrated the use of democratic rendering for multi-viewers in surround VR systems using dynamic zone, dynamic tiling and per pixel camera techniques. Although the rendering techniques provided a sophisticated result for multiple users, it still averages the users' position and rotation when the users look at a nearby point. Also, the per pixel camera technique has the drawback of slowing down the frame rate due to computation complexity.

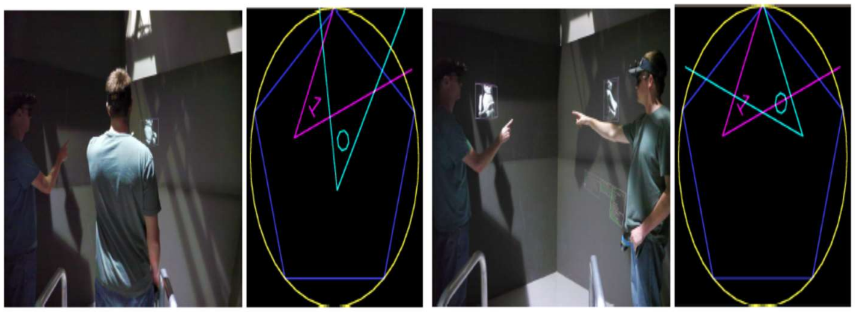

Figure 2.2.7. Two users looking in a different direction (left) and the same direction (right). When they look in the same direction (right), the final PoV is calculated by the average of the users' location. (Schulze 2012)

Tripicchio et al. (2014) compared six different tracking techniques (See Figure 2.2.8) for multi-user interaction and found that a MT method (where the PoV is averaged over all users) and a weighted mean tracking method (where a closer user has larger weight in deciding PoV) are the best ways for visual comfort and overall usability. In the MT method, the final point of view is determined by the equation: $\mathrm{PoV}_{final} = \sum \frac{1}{N} UserPosition$, where PoV_{final} is the final position of view and N is the number of users. In the weighted mean tracking method, a closer user contributes a higher weight to when computing the PoV.

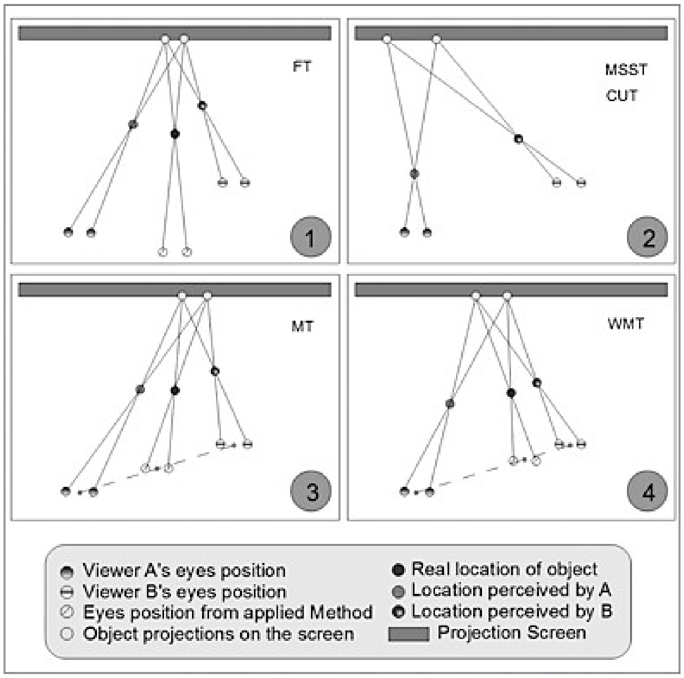

Figure 2.2.8. Schematic two-dimensional diagrams of common point-of-view calculation methods. FT, fixed tracking; MSST, manually switched single tracking; CUT, closer-user tracking; MT, mean tracking; WMT, weighted mean tracking. (Tripicchio 2014)

Simon (2007) conducted a qualitative and quantitative study comparing usability and interaction performance for multi-user interaction to tracked and non-tracked interaction for ray-casting selection and hand manipulation. He found that first-person interaction with a large-scale display without head-tracking was difficult to use. While interaction in a multi-viewpoint system had better performance than head-tracked interaction, interaction with head-tracking performed better than multi-viewpoint interaction in a simple manipulation task.

2.3 3D Visual Fatigue

Multi-user interactive visualization for a shared large-display using 3D stereoscopy can create visual fatigue. The common causes of visual fatigue from 3D stereoscopy and reduction approaches are discussed. In this section, the main causes of visual discomfort in 3D stereoscopy are introduced and the reduction techniques to reduce visual fatigue caused by one of the major causes, inappropriate disparity, are reviewed.

2.3.1 Visual discomfort

There are many literature reviews about the causes of visual discomfort in 3D stereoscopy. (Howarth, 2011; Tam 2012; Bando 2012; Urvoy 2013; Li 2015) and they introduced several main causes of visual discomfort from stereoscopy.

2.3.1.1 Crosstalk

Crosstalk is the incomplete separation of images when viewing stereoscopy, known as “ghosting” (See Figure 2.3.1) (Kooi 2004). Interference between images can cause Crosstalk. It usually annoys users to look at a scene and affects depth perception as well as visual comfort. Crosstalk can be reduced by changing the display hardware (Konrad 2000), heuristic thresholding (Sanders 2003), blurring (Ideses 2005), calibration (Sanftmann 2011) and so on.

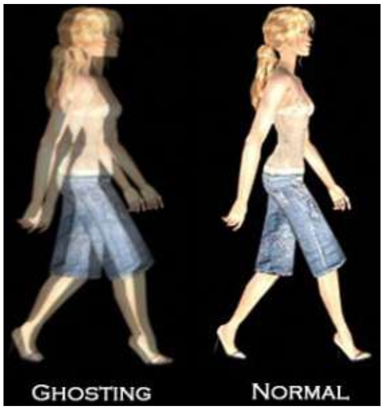

Figure 2.3.1. Crosstalk (ghosting, left) and normal scene (right).[15]

2.3.1.2 Depth of Field

Depth-of-Field is the depth range at which sharp shapes appears. In normal viewing, eyes converge on an object of attention and then the object is drawn into sharp focus (using the coupling between vergence and accommodation). The other objects behind and in front of the object become blurred. This process helps to prevent binocular rivalry and excessive disparities caused by being far from the plane of convergence. Figure 2.3.2 illustrates the difference between without depth of field and with depth of field.

The vergence varies depending on the disparity of targets, while the accommodation is fixed at the screen distance. The conflicting between the vergence and the accommodation, called vergence-accommodation conflict, makes the visual system more difficult to respond quickly and accurately compared to normal viewing. Artificial blurring technique can help reducing this discomfort and the vergence-accommodation conflict (Torii 2008; Carnegie 2015).

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[15] https://miriamruthross.wordpress.com/terminology/

Figure 2.3.2. Without depth of field (left) and with depth of field (right)[16].

2.3.1.3 Motion

Motion is another factor that can cause visual discomfort. Especially, fast motion in depth can create visual discomfort. Fast switching between crossed and uncrossed disparities may also affect visual discomfort. (Speranza 2006)

2.3.1.4 Inappropriate disparity

Inappropriate disparity is a major factor in visual discomfort, known as "on-screen disparity (parallax) or retinal disparity". It is caused by misalignment of left and right views and views with different projections. (Kooi 2004; Banks 2012). Excessive disparities are difficult to fuse left and right images, which disturbs to create depth perception and makes users discomfort.

2.3.1.5 Cardboard effect

Cardboard effect is a flattening effect on the screen caused by missing depth cues, small camera baseline, and limited depth resolution. This can be addressed by generating missing depth information using adaptive disparity mapping (Shibuhisa 2012). Figure 2.3.3 shows an example of the of adaptive disparity mapping suggested by Shibuhisa et al. Original 3D image (upper left), original disparity information (upper right), disparity information after modifying spatial layout (bottom left), and disparity information after

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[16] https://www.youtube.com/watch?v=P88t9Y94qSc

adaptive disparity mapping (bottom right).

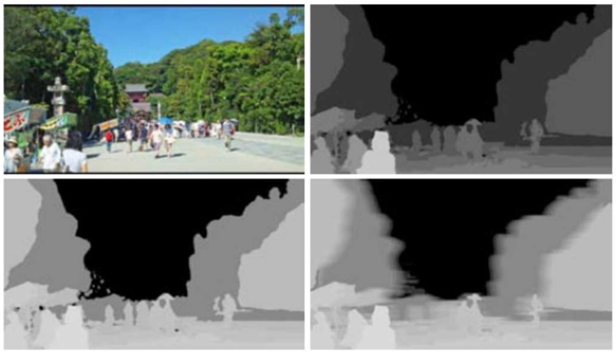


Figure 2.3.3. An example of adaptive disparity mapping (Shibuhisa 2012).

2.3.2 Inappropriate disparity

Although there are many factors that cause visual discomfort, inappropriate disparity is one of the major factors. To reduce the discomfort from inappropriate disparity, many techniques were developed. For example, there are various approaches for enhancing visual comfort by adjusting the depth range using view synthesis (Konrad, 1999; Kishi 2008; Ide 2010).

Early, Konrad (1999) developed a block-based linear interpolation method. This method interpolated the disparity map using a block window and compensated the big disparity among pixels.

Ide et al. (2010) presented a novel idea about how to maintain the 3D aspect ratio of 3D images for resizing or changing viewing window and display size. Using non-linear resize that alters the depth dependent disparity of 3D stereoscopy, they preserved skewed z-axis that causes visual comfort.

Scalable 3D image conversion technique was proposed by Kishi et al. (2008). Using an original parallax map, they adjusted the depth range and then built new parallax map. Figure 2.3.4 illustrated the concept of scalable 3D image conversion. Therefore, they could raise the comfort level of images by reducing excessive parallax using interview rendering methods.

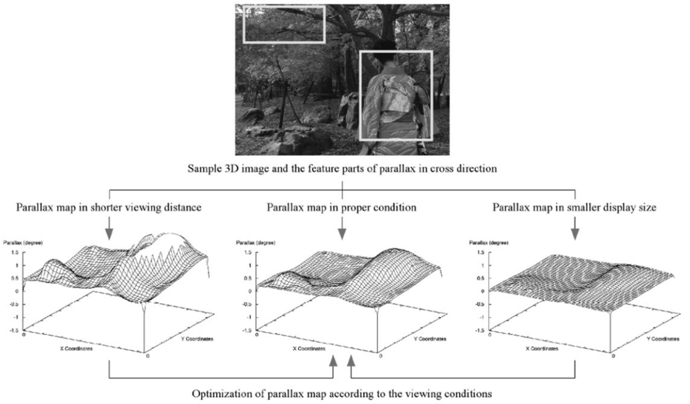


Figure 2.3.4. The concept of scalable 3D image conversion (Kishi 2008).

Holliman implemented non-linear depth scaling (Holliman 2004). He provided the improved depth perception in a defined region of interest compared to other regions of the scene. To find the interesting region, the position of view was tracked.

Another non-linear disparity mapping technique for stereoscopic 3D was developed by Lang et al. (2010). This technique used sparse correspondence and image warping with non-linear and locally adaptive depth mapping methods. This technique used temporal and special depth information in 3D videos and could reduce discomfort. Figure 2.3.5 depicted the original image and the result image after applying the non-linear remapping method.

Figure 2.3.5. Nonlinear disparity remapping. The original image (left) and nonlinearly remapped image. (Lang 2010)

Similar nonlinear mapping techniques were developed by Wu et al (2011).

They used the linear function for average image disparities and the nonlinear function for extreme disparities, which can improve the visual comfort level. Sohn et al. (2014) developed a technique combining global linear scaling with local nonlinear scaling for extreme disparity regions. Oh et al. (2015) estimated visual fatigue using disparity magnitude, disparity motion, and spatial frequency and then remapped the disparity with the nonlinear function.

Park et al. (2004) developed a novel technique to synthesize the virtual views at the location of the interval between two physical cameras. They could reduce visual discomfort by created depth information in empty depth area. Figure 2.3.6 showed the view synthesis procedure.

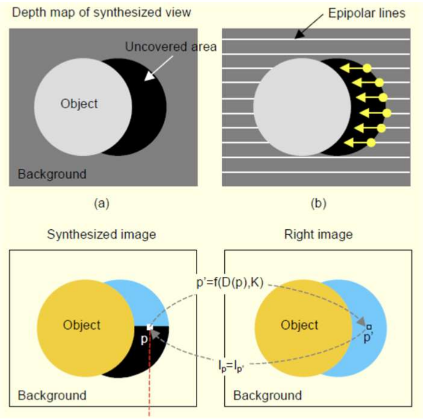


Figure 2.3.6. An illustration of the view synthesis procedure. (a) forward mapping, (b) directional interpolation of disparity map along epipolar line (Park 2004).

For 3D stereoscopy with mobile devices, Mangiat et al. (2012) investigated the effect of virtual camera separation on depth perception and realistic scenes for 3D stereoscopic handheld devices. They found less than 20mm camera separation for the zone of comfort in 3D handheld devices. Also, they investigated that 20mm for the camera separation provided more realistic 3D video for 3D video communication. The compared result is shown in Figure 2.3.7.

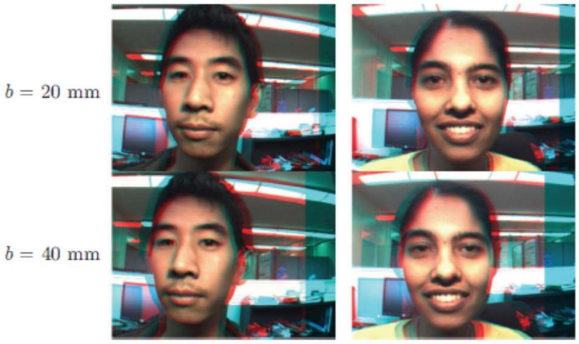


Figure 2.3.7. Comparison between two different camera separation for a handheld device. (Mangiate 2012)

2.4 Chapter Summary

This chapter reviewed previous research in 3D multi-user interactive visualization with a shared large-scale display focusing on the three main topics of this thesis: display setup, interactive visualization, and 3D visual fatigue.

Section 2.1 reviewed previous research on display setups for multiple users with a shared large-scale display, including related display interfaces. There are two types of display setups for multi-user interaction. SDG can provide a shared collaborate environment and increases the users' ability. On the other hand, MDG allows users to have private and independent views of the environment and distributed environment for collaboration. There were many applications and interaction techniques on co-located collaborative display interfaces to support seamless, effective and natural multi-user interaction. They mostly employed a shared view that enables users to access the whole space on the screen together or a multi-view that provided independent views. Also, many researchers developed novel display interfaces and evaluated their interfaces by comparing a shared view and a split screen. However, several advantages and disadvantages of a shared view and a split screen display setup for multi-user interaction were briefly discussed. To explore the effect of display setups and the relationship between display setups and multi-user interaction, Chapter 3 investigates display setups for multi-user visualization.

Section 2.2 described previous works on interactive visualization with a shared large-scale display for multiple users. Many visualization techniques with a shared large-scale display for multiple users have been developed in order to support interactive visualization, effective collaboration, and less visual fatigue. However, they still have limitations such as requiring special hardware and limiting the individual user's view. Most multi-user interactive visualization systems employed the MT method because it could reduce visual discomfort. However, the MT method cannot reflect individual users' movement effectively for visualization as the PoV is calculated using the average of multiple users' locations, which makes the movement of the PoV less than the physical traveling distance. In stationary tasks where users do not need to travel frequently, such as object manipulation, the MT method could be tolerable. However, in applications requiring frequent movements, such as spatial exploration, the MT method may not be the optimal solution. To overcome the limitation of the MT method, Chapter 4 introduces interactive visualization techniques for multiple users and evaluates the combination of these methods.

In section 2.3, the author introduced the main causes of the visual fatigue from 3D stereoscopy and previous works on reducing the users' fatigue. There are a number of primary causes that create visual fatigue in a visualization system using 3D stereoscopy, including crosstalk, depth of field, motion, inappropriate disparity, and the cardboard effect. Inappropriate disparity is the one of the major causes and many techniques has been developed to reduce this. These approaches to reduce visual comfort from inappropriate disparity can be categorized into depth (disparity) remapping techniques, generating empty depth information, and adjusting camera separation. The depth remapping techniques can decrease the overall depth perception. Also, they are computationally complex or some approaches require sequential information to adjust the depth map. The generating empty depth information approach may not be the optional solution for the real-time virtual environments because it requires more computation. In a virtual environment, the depth information can be easily obtained using a depth buffer as well. The fixed camera separation approach for handheld devices may not give immersive 3D depth perception in general virtual environment due to the short interpupillary distance. The previous research could reduce visual discomfort effectively although they have several limitations. It requires more computation or more information to adjust disparity information, which may not be suitable for a real-time virtual environment. It is also possible to degrade overall depth perception. In Chapter 5, the author proposes a method for adaptively and automatically adjust the IPD according to the configuration of the 3D scene, so that the visualization can maintain sufficient stereo effect while reducing visual discomfort.

The next Chapter introduces common display setups for multiple users and discusses the effect of display setups and the relation between display setups and multi-user interaction.

Chapter 3

Display Setups for Multiple Users

This chapter discusses how to setup a shared large-scale display for multiple users. As explored in Chapter 2, the shared view setup has been widely used with a shared large-scale display. This display setup enables users to share their attention and to facilitate collaboration and increases users' ability to collaborate. The split screen setup has been employed in the television industry more than in VR and it can provide an individual screen to increase independency. In previous research, several advantages and disadvantages of a shared view and a split screen display setup for multi-user interaction have been discussed (McGill 2015), but they were not explored in detail. In contrast, this chapter investigates the effect and the relationship between display setups and multi-user interaction in detail.

In this chapter, a shared view and a split screen display setups are discussed. To overcome the weak point of a split screen display setup, navigation information will be introduced. To evaluate each display setup for multi-user interaction, the display setups were designed and implemented with a shared large-scale display. From the results of the user study, several design considerations are provided for display setups for multi-user interaction.

In the remainder of this chapter, firstly, the designed and implemented display setups are explained in detail. Then, the experimental conditions and procedure are described to evaluate the interaction performance, usability, and preference of the display setup. Finally, the experimental results are discussed and conclusions are presented.

3.1 Display setup

In this section, the three display setups that were designed and implemented for the experiment are explained. Two display setups are widely used in multi-user interaction with a shared large-scale display; a shared view and a split screen. The third setup includes navigation information in addition to the split screen.

3.1.1 Shared View

A shared view is commonly used for a shared large-scale display composed of a single display or multiple displays. Users can share the same visualization or information and manipulate it at the same time. The advantages of a shared view are to utilize whole display for visualization and interaction and to increase collaborative experience. On the other hands, one of the disadvantages of the shared view is a control conflict between users. Because the users can access the environment at the same time, users can interfere others' interaction. Therefore, several control interfaces or strategies were developed to reduce the control conflict such as negotiated access (requiring an additional action such as '*click*' to hand over control) and fixed access (a system assigns control to each user automatically) (Gutwin 1998; Wallace 2009).

3.1.2 Split Screen

A split screen setup is another common setup for a shared large-scale display. This setup provides an independent view and separate control to each user which increases the user's interaction freedom. However, this setup cannot support private views like a multi-view display and users can also lose their focus on their own view when they look at other user's screens. The setup also splits the whole screen, so that it reduces the size of the workspace for each user. Due to the independent views, it is hard for each user to recognize the locations and direction of other the users in VE exploration or manipulation tasks.

3.1.3 Split Screen with Navigation information

The third setup overcomes one disadvantage of the split screen by adding navigation information (NI) in order to provide a common reference frame for the location of users. The NI can provide additional information on the location of users in relationship to each other and facilitate shared exploration and manipulation. In a pilot study, the participants used a shared view and a split screen for the manipulation tasks in the experiment. The participants had a problem with finding their location and the route to reach a certain location. For instance, when the participants needed to rotate -30 degrees to complete the task, they rotated 330 degrees because they did not know the direction to the shortcut. One of the main problems of a split screen with a shared display is that it is hard for users to know where they are in the displayed VE and how to reach a certain place. However, navigation information could help to find locations of users and a faster route, even if it occupies additional screen space.

3.2 Experiment

The aim of our study was to design, develop and evaluate display setups with a shared large-scale display for multi-user interaction. With a shared large-scale display, the author investigated how display setups facilitate or impede multi-user interaction. To explore the effects of display setups, the control interfaces were restricted and were not used for personal visualization.

The study had the following aims:

- To learn how multiple users interact with a shared large-scale display depending on the display setup.

- To investigate the difference between a shared view and a split screen display setup in terms of usability workload, and ability to collaborate.
- To investigate if navigation information can affect multi-user interaction.

In order to accomplish these aims, the author designed and built the three different display setups mentioned in the previous section. This experimental system has the capability to allow two users to interact with the systems using individual tablets.

The experiment used the *VisionSpace* system mentioned in Chapter 1. The setup is as shown in Figure 3.2.1.

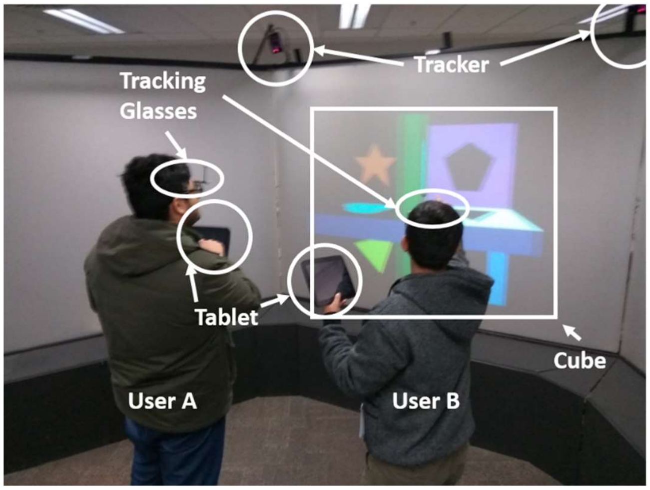


Figure 3.2.1. Experimental Setup.

Two tablets were provided to manipulate the 3D virtual objects in the virtual environment. The mobile tablets were only used to detect touch gestures and did not display any visualization, information, or graphic user interface (GUI) to take attention from the large screen.

The tablet interface provided users with two different modes (manipulation and cursor mode) and four touch gestures (double tap, swiping, pinching in/out, and holding tap) for the experiment. The manipulation mode and cursor mode can be switched between using the double tap gesture. In the manipulation mode, the participants can rotate the 3D object on the screen with a swiping gesture, and zoom in/out with a pinching in/out gesture. In the cursor mode, the cursors (a red sphere and a green sphere for each user) are displayed on the screen. Each participant could select a shape on the 3D object using their cursors. The participants could also move their own cursors with the swiping gesture and select the shape on the cube with the holding tap gesture.

At the beginning of each condition, the participants were asked to stand at marked locations on the floor, at each center of the split screen (See Figure 3.2.1). When the experiment started, a large 3D object comprised of 24 images was displayed on the large screen. Each surface of the object contained 4 images and each edge of the object was reentrant to minimize the number of images that the participants could view at once (See Figure 3.2.2). This encouraged the participants to rotate the object more. Each image was a color-filled shape or black-colored shape with a colored background. For the tasks in the experiment, the participants were asked to find the matching shapes, as shown in Figure 3.2.3. The detailed procedure of the experiment will be explained in the experimental procedure section.

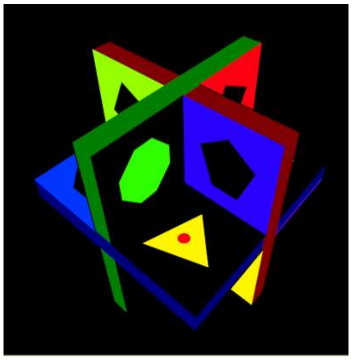


Figure 3.2.2. An example of a 3D object for the experiment.

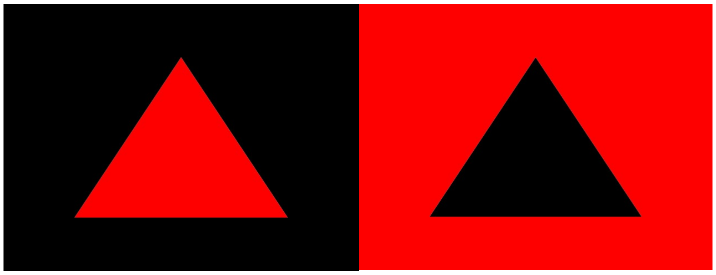


Figure 3.2.3. Red triangle shape (left) and black triangle shape with red background (right).

3.2.1 Experimental Conditions

The study design incorporated three conditions:

(1) Shared view with two control interfaces. A comparative baseline for typical multi-user interaction with a shared large-scale display (SV).

(2) Split screen with two control interfaces, which allows each user to interact with each split screen independently (SS).

(3) Split screen with two control interfaces and navigation information, which provides the location of each user's point of view (SSNI).

In the shared view condition, both participants could move their cursors over the entire screen in the cursor mode. In the manipulation mode, the participants could have a conflict to rotate or to zoom in/out the object. To avoid the conflict, they needed to notify to their partner to manipulate the object or needed to make their strategies. For example, only one participant rotates the object.

In the split screen condition, each user had an independent workspace. At all times the participants could manipulate the object and independently move their own cursors. In cursor mode, their cursors could not cross over to the partner’s workspace.

The split screen with navigation information condition provided navigation information in addition to the split screen condition. The navigation information was displayed at the bottom of the screen. Users could use it for finding a faster route or advising the route or the location for their partner. Figure 3.2.4 shows the difference between each condition.

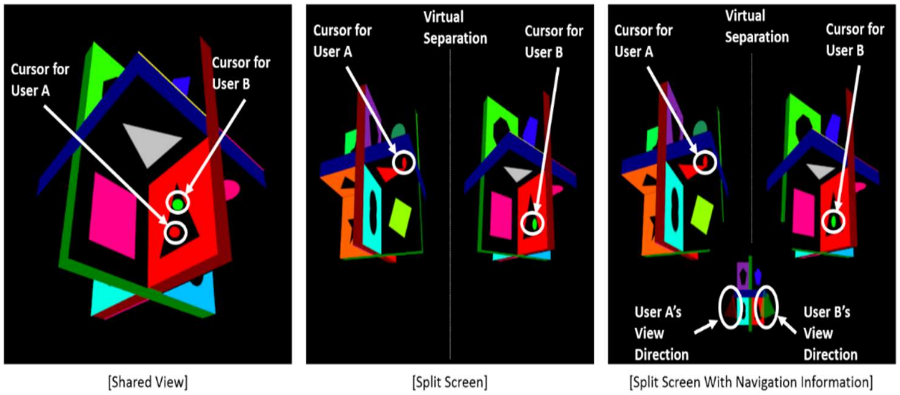


Figure 3.2.4. The differences between each condition.

3.2.2 Experimental Procedure

A single task in the experiment was similar to a block matching game. If one participant selected the color-filled shape, his/her partner needed to select the same shape in black with the background in the same color. For example, if one participant selected the red triangle shape, his/her partner needed to select the black triangle shape with a red background (see Figure 3.2.3).

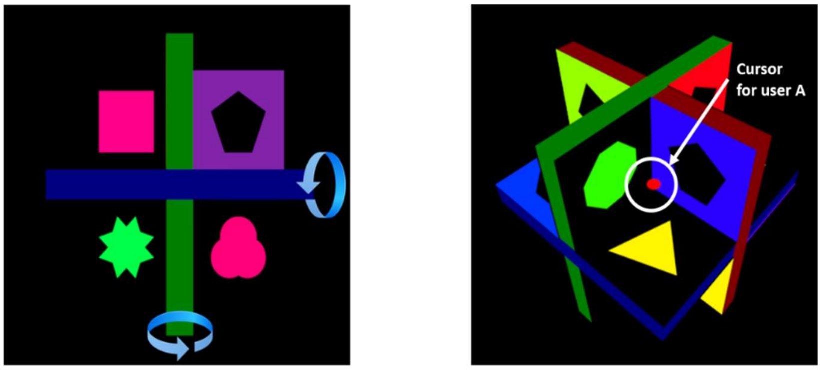
The experiment consisted of two parts; manipulation for finding matching shapes and selection of matching shapes. With the SS and SSNI conditions, participants could manipulate the 3D object and select the matching shape individually. With SV, the participants could manipulate the 3D object together and each participant had to individually select the matching shapes.

This was to prevent only one participant finishing the whole task.

The detailed procedure for each single task is explained in Figure 3.2.5. When the experiment started, the large screen displayed a large 3D object in one of the display setups (SV, SS or SSNI). The participants were asked to find the matching shapes in the 3D object by rotating it and zooming in/out using the manipulation mode (Step 1 in Figure 3.2.5). After identifying the matching shapes, the participants were asked to change the mode from the manipulation mode to the cursor mode (Step 2 in Figure 3.2.5) with the double tap gesture. In the cursor mode, a small colored sphere was shown as a cursor. Each user could switch to the cursor mode independently and each had his/her own cursor in a different color. User A, who stood at the left side of the screen, had the red cursor and User B, who stood at the right side of the screen, had the green cursor. After changing to the cursor mode, the participant had to place his/her cursor on the shape with the swiping gesture (Step 3 in Figure 3.2.5). In step 4, the participants were asked to select the shape by using a tap gesture. As shown in step 4 in Figure 3.2.5, the selected shape was displayed on the left (for User A) or the right (for User B) top corner of the screen.

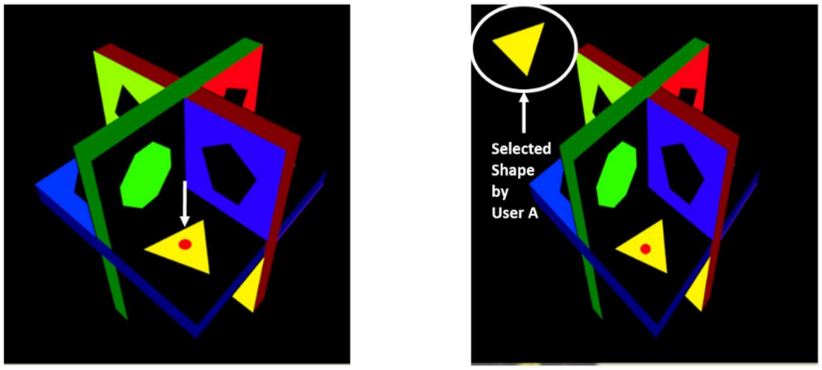
In a shared view condition, participants could follow the steps together or one by one depending on the location of the matching shapes. For example, if the matching shapes were shown in the view at the same time, the participants could move their cursors and selected the matching shapes at the same time. If not, one participant needed to select the shape and then another participant could select the matching shape to complete the task after manipulating the structure. In the SS and the SSNI condition, the participants could do the series of procedures independently. To complete the task, the participants needed to select the matching shapes as shown in Figure 3.2.6. This was the process of a single task for the experiment. The participants were asked to find as many matching shapes as possible for 5 minutes in each condition.

Note that the procedure and the goal for all three conditions were basically same, and the difference between the shared view condition and the split screen conditions was independency. With the shared view, the participants could select matching shapes either together or sequentially. With the split screen, the participants could independently find and select the matching shapes.



A. Step 1. Find the matching shapes by rotating and zooming in/out with the manipulation mode

B. Step 2. After finding the matching shapes, double tab to switch to the cursor mode. In the cursor mode, the small sphere(red or green) will be shown on the screen.



C. Step 3. Place the sphere cursor on the shape by swiping gesture in the cursor mode.

D. Step 4. Hold tab on the image and the selected shape will be display on the left or right top.

Figure 3.2.5. The detailed procedure of a single task.

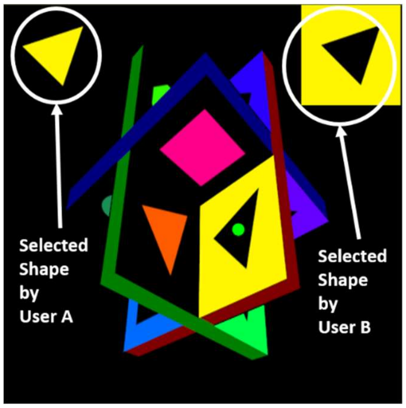


Figure 3.2.6. An example of the completed task with a shared view condition

3.3 Experimental Measures

To determine the effects on users' abilities to effectively collaborate, the study collected the task completion time per task (*tct*), and touch distance that participants used to interact with mobile tablets via touch gestures (swiping and pinching in/out). Post-condition questionnaires were also given using 7-point Likert scale questions (1 = strongly disagree and 7 = strongly agree) from previous research (WebSurface (Tuddenham 2009), Mobisurf (Serifert 2012), WeSearch (Morris 2010) and Permulin (Lissermann 2014)). WS, MO, WE, and PE denotes the questions from WebSurface, Mobisurf, WeSearch, and Permulin, respectively. The questions asked are in Table 3.3-I.

Table 3.3-I. Asked questions from the previous research.

Previous Research	No.	The Questions
WS	1	We were able to collaborate effectively
	2	We were able to work independently to complete the task
	3	It was easy to discuss the information we found
	4	We were able to work together to complete the task
	5	We were able to work together to complete the task
MO	1	How well did the system support collaboration?
	2	How well did the system support you to share particular information with your partner?
	3	I was able to tell when my partner was looking at what I was browsing?
	4	How well did the system support you to see/review what your partner was talking about?
WE	1	The system was helpful in completing the given task
	2	I was aware of what my partner was doing
PE	1	My partner was aware of what I was doing

The study also measured the workload for each display setup using the NASA-TLX survey (Hart 1988) and usability using the System Usability Scale (SUS) (Brooke 1996). After completing all conditions, participants were asked to rank the three display setups based on their preference and to write comments about their experiences.

A repeated measures ANOVA ($\alpha = 0.05$) with a Greenhouse-Geisser correction was employed using SPSS for analyzing the effect of different display setups on task completion time per task (*tct*), touch distance, NASA-TLX, and SUS. A non-parametric Friedman test was applied in order to analyze the post-condition questionnaires and preference with α level of 0.05. Post-hoc tests using Wilcoxon signed-rank tests with the Bonferroni correction (Bonferroni 1936) (α = 0.017) were applied.

The study recruited 42 participants (22 males and 20 females) aged 21 to 38 years old (Mean (M) = 26.67, Standard Deviation (SD) = 4.97). All participants had experience with a mobile interface such as smart-phone or a tablet, 50% of the participants had prior experience with a 3D stereoscopic visualization like 3D movies, and 57% of the participants had experienced large-scale virtual environments such as CAVE-like systems.

3.4 Results

The results revealed that a shared view could increase the collaboration performance even though both participants could not control the 3D object at once. The SSNI condition enabled users to use less touch gesture interaction compared to the other conditions. The result of the System Usability Scale showed that there was no significant difference between conditions. The participants had more mental demand and frustration with the shared view while the overall workload was similar for all conditions. The results of post-condition questionnaires showed that the split screen could increase independency and the comparison of the previous work showed that providing individual devices may increase the usability and workload. The SSNI was most preferred compared to the other display setups.

3.4.1 Task Completion Time Per Task

Figure 3.4.1 shows the average task completion time per task for the three experimental conditions. As shown, the SV condition results in the shortest task completion time (Mean (m) = 18.569s, Standard Deviation (SD) = 3.448s) while the SS condition provided the longest duration per task (M = 24.463s, SD = 4.738s).

A repeated measures ANOVA test with a Greenhouse-Geisser correction showed that there was a significant difference between conditions (F (1.983, 39.662) = 12.099, p < 0.001*[17]). Post hoc tests using the Bonferroni correction revealed that collaboration with SV was faster than other conditions, which was statistically significantly different from SS (p = 0.001**) and SSNI (p = 0.002**). Although not statistically significant (p = 0.959), navigation information elicited a slight reduction in task completion time (SSNI: M = 23.826s, SD = 5.645s) from the split screen condition (SS: M = 24.463s, SD = 4.624s).

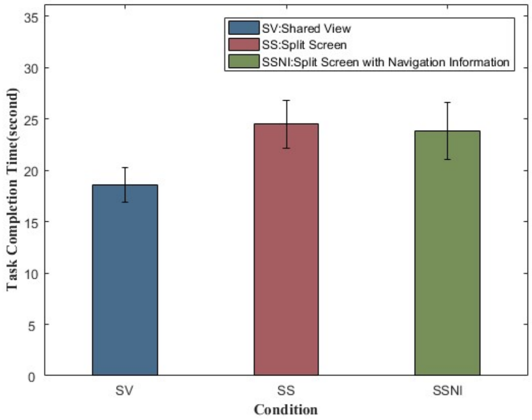


Figure 3.4.1 Average task completion time per task. (Bar represents standard deviation)

3.4.2 Touch distance

There was significant difference between display setups (F (1.346, 26.921) = 13.577, p < 0.001*) in touch distance. Participants with a shared view used less touch gesture interaction compared to the other display setups (SV: M = 1328.1 pixels, SD = 353.5 pixels, SS: M=1998.6 pixels, SD=572.1 pixels, and

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[17] *$p < 0.05$, **$p < 0.017$*

SSNI: M=1562.9 pixels, SD=298.6 pixels). A post hoc test using the Bonferroni correction showed that the SV condition required significantly less touch gesture interaction compared to the SS condition ($p < 0.001$**) and the SSNI condition ($p = 0.042$**). In addition, navigation information reduced the touch distance from 1998.6 pixels to 1562.9 pixels, which was significantly different from the SS condition ($p = 0.049$**). Figure 3.4.2 presents the average total touch distance for all conditions.

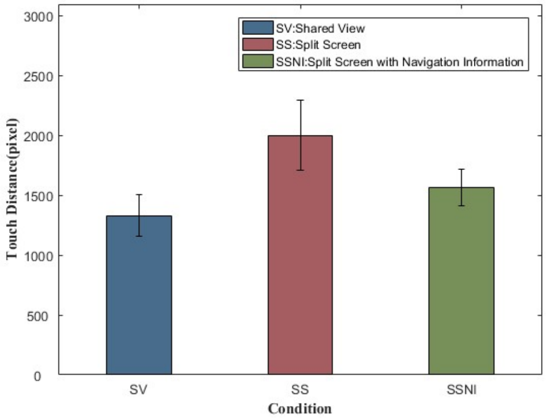


Figure 3.4.2. Average touch distance for all conditions. (Bar represents standard deviation)

3.4.3 System Usability Scale

The results of system usability scale shown in Figure 3.4.3 revealed that collaboration with a split screen had the highest usability score (M = 75.23, SD = 11.29). However, the results for all conditions were very similar (SV: M = 74.28, SD = 10.58, and SSNI: M = 74.47, SD = 9.01) and a repeated measures ANOVA found no significant difference between the conditions ($F(1.944, 38.883) = 0.071$, $p = 0.927$).

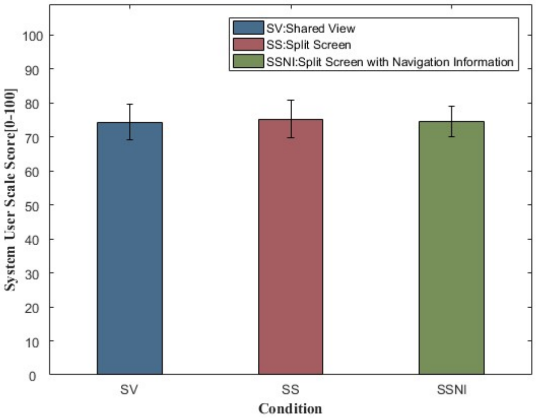


Figure 3.4.3 Average System User Scale Score for all conditions. (Bar represents standard deviation)

3.4.4 NASA-TLX

Figure 3.4.4 and Figure 3.4.5 illustrate the experimental results of subscales of NASA-TLX and average overall score for the three conditions, respectively. A repeated measured ANOVA test showed the physical demand, temporal demand, performance, and effort scores were not significantly different between the conditions, as shown in Table 3.4-I. However, the results of mental demand and frustration did differ significantly between the conditions (Mental demand: F (1.893, 37.850) = 4.013, $p = 0.028$, frustration: F (1.384, 27.688) = 3.785, $p = 0.049$). A post hoc test revealed that splitting a screen significantly reduced mental demand ($p = 0.049$) and navigation information did not have a significant effect on mental demand, although it increased slightly ($p = 0.596$). Similar to the results of mental demand, a significant difference was found in frustration by a repeated measured ANOVA (F (1.384, 27.688) = 3.785, $p = 0.049$). According to the statistical analysis by post hoc tests, neither splitting the screen ($p = 0.445$, between a shared view and a split screen) nor adding navigation information ($p = 0.717$, between SS condition and SSNI condition) significantly affected the frustration, when both split screen and navigation were applied together it reduced frustration ($p < 0.001$).

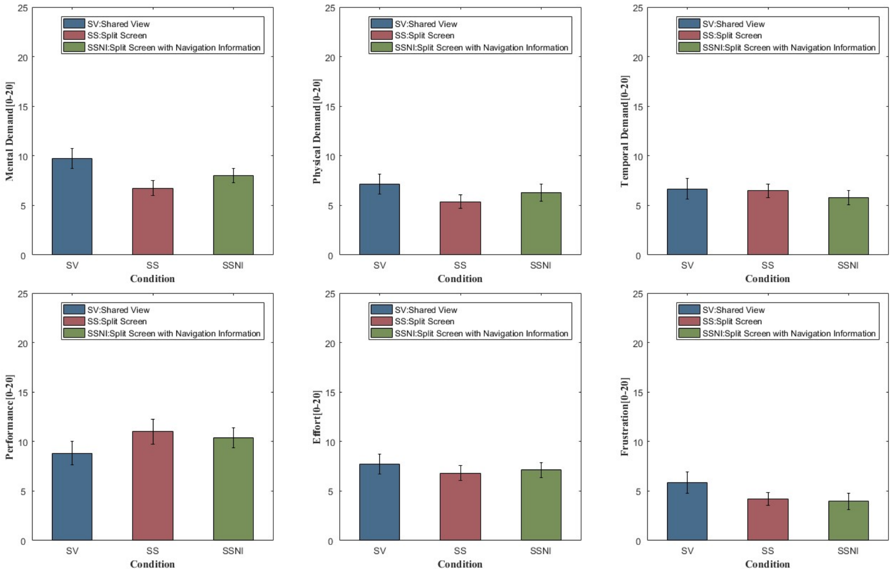


Figure 3.4.4. The results of the NASA-TLX subscales. (Bar represents standard deviation)

Table 3.4-I. Statistical results of NASA-TLX subscales.

Subscales	**Repeated measures ANOVA**	**Post hoc tests**		
		SV - SS	**SV - SSNI**	**SS-SSNI**
Mental Demand	F (1.893, 37.850) = 4.013, p = 0.028*	p= 0.049**	p = 0.215	p = 0.596
Physical Demand	F (1.991, 16.390) = 1.265, p = 0.293	NA	NA	NA
Temporal Demand	F (1.848, 36.952) = 0.317, p = 0.713	NA	NA	NA
Performance	F (1.712, 34.240) = 1.042, p = 0.354	NA	NA	NA
Effort	F (1.808, 36.167) = 0.315, p = 0.710	NA	NA	NA
Frustration	F (1.384, 27.688) = 3.785, p = 0.049*	p = 0.445	p= 0.001**	p = 0.717

**p < 0.05, **p < 0.008*

A repeated measured ANOVA was carried out for overall NASA-TLX. There was no significant difference between conditions (F (1.553, 31.055) = 1.026, p = 0.353) although the mean values showed a trend of decreasing as the split screen and navigation information were applied.

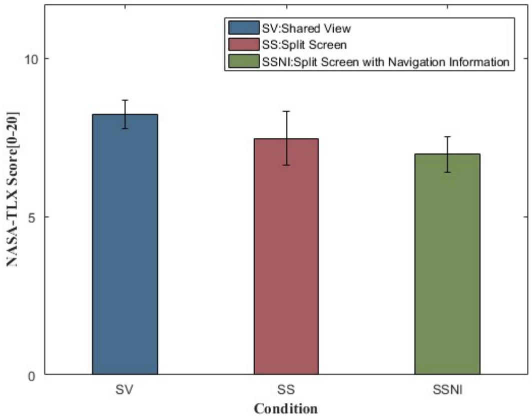


Figure 3.4.5 Average overall NASA-TLX scores. (Bar represents standard deviation)

3.4.5 Questionnaires

The Friedman test determined that the results of the WE-2 questionnaire between display setups were significantly different ($X^2 = 16.419$, $p = 0.001$*). A post-hoc analyses with the Wilcoxon signed-rank test with the Bonferroni correction was carried out and significant differences were found between the shared view and the split screen conditions ($Z = -3.642$, $p < 0.001$**) and between the shared view and the screen split with navigation information conditions ($Z = -3.484$, $p < 0.001$**).

Compared to the previous study, only the result of the WE-2 question was similar and the other results were different. This will be discussed in the discussion section in detail. Table 3.4-II shows a detailed statistical analysis for all questions.

Table 3.4-II. Statistical results for all conditions and comparison with the result of the user study by McGill et al. 2015. “1-2” denotes that there was a significant difference between condition 1(SV) and condition 2(SS).

Questions	Condition			Friedman Test	Willcoxon Post-hoc			The results of Wilcoxon Post-hoc test in (McGill et al. 2015)
	1: SV	2: SS	3: SSNI		1 vs 2	1 vs 3	2 vs 3	
WS-1: We were able to collaborate effectively	4.976 (1.112)	4.952 (0.669)	5.166 (0.619)	$X^2 = 1.768$ ($p = 0.413$)	NA	NA	NA	1-2
WS-2: We were able to work independently to complete the task	3.166 (1.028)	4.809 (0.580)	4.714 (0.902)	$X^2 = 18.759$ ($p = 0.001$*)	-3.642 0.001**	-3.484 0.001**	-0.583 0.560	1-2
WS-3: It was easy to discuss the information we found	4.904 (0.664)	4.833 (0.764)	4.928 (0.712)	$X^2 = 1.138$ ($p = 0.566$)	NA	NA	NA	None
WS-4: We were able to work together to complete the task	4.976 (0.641)	4.976 (0.782)	5.071 (0.576)	$X^2 = 0.026$ ($p = 0.987$)	NA	NA	NA	1-2
WS-5: I was able to actively participate in completing the task	5.095 (0.624)	5.261 (0.374)	5.142 (0.635)	$X^2 = 0.226$ ($p = 0.893$)	NA	NA	NA	1-2
MO-1: How well did the system support collaboration?	4.261 (1.020)	4.690 (0.732)	4.642 (0.823)	$X^2 = 1.707$ ($p = 0.426$)	NA	NA	NA	1-2
MO-2: How well did the system support you to share particular information with your partner?	4.714 (0.830)	4.523 (0.749)	4.428 (1.003)	$X^2 = 0.775$ ($p = 0.679$)	NA	NA	NA	None
MO-3: I was able to tell when my partner was looking at what I was browsing?	4.761 (0.956)	4.476 (0.980)	4.285 (1.113)	$X^2 = 3.397$ ($p = 0.183$)	NA	NA	NA	None
MO-4: How well did the system support you to see/review what your partner was talking about?	4.619 (0.934)	4.690 (0.858)	4.214 (0.943)	$X^2 = 0.329$ ($p = 0.848$)	NA	NA	NA	None
WE-1: The system was helpful in completing the given task.	4.667 (0.953)	4.190 (1.308)	4.690 (1.018)	$X^2 = 2.553$ ($p = 0.279$)	NA	NA	NA	1-2
WE-2: I was aware of what my partner was doing	4.214 (1.168)	4.4762 (0.901)	4.571 (0.746)	$X^2 = 1.900$ ($p = 0.387$)	NA	NA	NA	None
PE-1: My partner was aware of what I was doing	4.466 (0.953)	4.214 (1.318)	4.714 (0.943)	$X^2 = 1.293$ ($p = 0.529$)	NA	NA	NA	None

3.4.6 User Preference

Figure 3.4.6 shows the average user preference response for three display setups. A Friedman test revealed that there was a significant difference between display setups ($X^2 = 16.419$, p = 0.001*). The post-hoc analysis with the Wilcoxon test found that the result for the SSNI condition differed significantly from SV (Z = -2.856, p = 0.004**) and SS (Z = -2.408, p = 0.016**) while the result of the SS condition was not significantly different from the SV condition (Z = -1.471, p = 0.141).

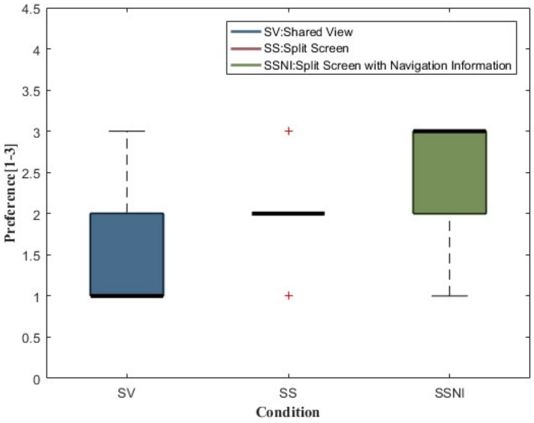


Figure 3.4.6. Average preference scores for all conditions (High score means more preferred).

3.5 Discussion

The results of the preference showed that participants felt that the split screen with navigation information condition was preferable over the shared view and the split screen conditions. Most participants voted the shared view as the worst display setup because of the physical bottleneck of sharing the control. The participants preferred an independent view and navigation information. The participants answered that they felt more confident when they had more information such as their partner's view and navigation information.

The two main reasons for the preference result were independency and performance, which was expected. However, the performance with the split view (either with navigation information or not) was not superior to that with the shared view. When the number of completed tasks were revealed to the participants after the experiment, most participants were surprised and they thought that they would have completed more tasks with the split screen. The most participants said, "*I thought that I completed the more tasks with the independent view than with the shared view*". The results and their comments imply that the split screen display setup could increase the users' confidence level.

The results of the performance revealed that the shared view could increase collaboration performance. The interaction with the shared view provided the best performance compared to the other display setups. They had less misunderstanding such as wrong pointing (confused which screen the user mentioned) because the participants could search matching shapes and discuss it while looking at the same view. Therefore, they were able to finish the tasks faster. On the other hand, interaction in the SS and SSNI conditions took more time than in the SV condition. The author observed that the participants spent more time looking at their partner's view to search and match the shapes. If more information was available that helps to solve the problem, such as the partner's view and the navigation information are given, the participants tried to use them. The participants did not use a simple "peeking" action that the previous works discussed (McGill 2015), rather it was more of "reading" or "understanding" actions in collaboration because they stopped rotating the 3D object and tried to match their partner's shapes and their own shapes. The participants also occasionally missed the matching shapes on their own individual views due to the reading action, which made then spend more time in solving the puzzle. Therefore, the participants were more satisfied with more information, but they spent more time to use the information. In the SSNI condition, the participants also spent more time to view all of the visualization, but the navigation information was helpful, decreasing the task completion time.

From the touch distance results (the amount of touch gesture interaction used to manipulate objects), navigation information enabled the users to use their mobile tablet less since it provided a faster route. From the participants' feedback, the navigation information was helpful in some cases, although not always when the matching shapes were shown in the view at the same time. The results of the task completion time per task and touch distance implied that the navigation information could provide effective touch interaction. However, the split view with navigation information condition did not provide the best performance because the participants lost attention and they needed more time to understand the information.

The result of the System Usability Scale score showed that the display setups did not affect the usability. The average result of the display setups is greater than 70, which is a C grade and a "good" score. In previous research (McGill 2015), a shared view had an F grade, which is a "poor" score. The SUS scores in this study were similar between the shared view and the split screen while the result was different from the previous study (McGill 2015). Although the task in this study is slightly different from the previous study, it is basically similar to the task in the previous work. The difference between a single controller and individual controllers could have contributed to this improved result. If users have individual devices, this appears to increase usability even though they could not interact with the system at the same time.

The participants had more mental demand and more frustration when they collaborated using the shared view according to the NASA-TLX subscale results. While the navigation information also increased mental demands slightly, it did not significantly affect the mental demand level. The participants felt less frustration in the SSNI condition compared to the other display setups. The participants answered that they felt more confident if they have more information to complete the tasks. From the result, both the split screen and navigation information influenced frustration while each single component did not reduce the frustration level. However, the overall result of NASA-TLX showed that the mental demand and the frustration did not have a significant effect on the overall workload.

The result of the WS-2 questionnaire showed that the shared view could reduce independency enough for each user. The other results showed that there was no significant difference between the display setups while they had slight variations. Compared to a previous study (McGill 2015), most questionnaires had different results. This could be because the provision of individual devices could have influenced the capability for collaboration. From the interviews, participants did not feel strong frustration because they thought that they could use the controllers when they wanted to interact with the system. The problem of using a single shared controller is that users cannot access the controller when they want. In this case, they needed to ask their partner as well as to hand over the controller, which may make users frustrated or annoyed to collaborate. If they have their own device, this could increase users' confidence level even if they cannot interact with the system all the time. The difference between the shared view and the split view in the previous study (McGill 2015) may have resulted from the control problem.

3.6 Insights for Display Setups

From these results, there are several design considerations that can be made about display setup for a shared large-scale display for collaboration.

The split screen setup increases independency although users can lose attention and spend more time with it. The split screen setup provides individual views and users can share the individual screens as needed. This can increase user satisfaction level and reduce mental demand. However, looking at the partner's view could decrease user interaction performance, as previous studies have shown, when the being aware of the partner's view is related to completing a task, the users can lose more attention and need to spend more time on the partner's view. From the lost attention, overall performance can be decreased.

The shared view setup can provide effective interaction and collaboration. The shared view setup can increase interaction performance, although it may have an effect on mental demand and increase frustration due to the physical bottleneck for accessing the system. The shared view cannot provide an individual interaction workspace for each user, but can provide a shared virtual environment effective for discussion and collaboration. The access bottleneck and negative effects of a shared view could also be reduced by providing individual control devices. With users' compromising and discussing with each other, the access bottleneck can be minimized.

Navigation information can increase confidence level. In manipulation or exploration tasks, navigation information can improve the split screen display setup and help users to find their location and a faster route to the problem solution. This benefit reduces the amount of touch interaction required for a navigational task. However, the users need more time to understand the information they are seeing so that they cannot expect a significant performance increase. While navigation information is not always useful, users prefer having it available.

The split screen setup together with navigation information can influence frustration level. If the split screen and navigation information are provided together, the frustration level can be reduced. If users have more information to collaborate, it can increase confidence and decrease frustration. However, it can also increase mental demand.

Display setups may not have a big impact on usability and workload. If users have individual control devices that they can interact with at any time, the display setups may not influence overall usability or workload. The usability and workload may be influenced by control interfaces rather than display setups.

3.7 Conclusion

In this chapter, three different multi-user large-scale display setups for collaboration were introduced and evaluated. From the experiment results, several considerations for designing a virtual environment with a shared large-scale display were suggested. The experimental results showed that the shared view display setup does not critically disturb collaboration. Rather, it can provide an effective environment for collaboration. The split screen display setup can provide independent collaboration while it can take attention and require more time to collaborate. Also, it may lead to misunderstandings such as wrong pointing. The navigation information can reduce the interaction required for the navigational task, but an overall performance increase cannot be expected.

From the experiment results, a shared view was employed for multi-user interactive visualization that is discussed in next chapter due to the advantages of the shared view. The split screen and the split screen with navigation information can improve user confidence and reduce frustration level and they are more preferred than a shared view. However, a shared view can still provide effective interaction and collaboration and the display setups do not have a large impact on usability and workload. Next chapter explores interactive visualization with a shared view for multiple users.

Chapter 4

Interactive Visualization for Multiple Users.

This chapter explores interactive visualization for multiple users. According to the research review in Chapter 2, the Mean Tracking (MT) method is a common tracking method for multi-user visualization and many multi-user interaction systems often employ the MT method that averages location of all the users to create a single Point of View (PoV) because it can reduce visual sickness for users. However, it is not able to efficiently reflect individual users' movement because the PoV is calculated using the average of multiple users' locations, which makes the movement of the PoV less than the physical traveling distance. In stationary tasks where users do not need to travel frequently, such as object manipulation, the MT method could be tolerable. However, in applications requiring frequent movements, such as spatial exploration, the MT method may not be the optimal solution.

To overcome the limitation of the MT method, the author proposed a novel method combining the Object Shift Technique (OST) and the Activity-based Weighted Mean Tracking (AWMT) method. Compared to earlier research, the proposed method is novel in several ways. First, OST can vary the user travel distance with less visual fatigue by translating virtual objects corresponding to PoV. Second, the author uses the AWMT method where active users are given more weights compared to stationary users to calculate the PoV. In comparison, previously the weighted mean tracking method was based on the distance of users to a screen while the proposed AWMT method is based on the user’s activity, making it better in interactive visualization.

The OST can improve the user's mobility in multi-user VEs without increasing visual fatigue. The AWMT method can help increasing the user's mobility with the OST. Finally, the author evaluated the combination of these two methods in terms of effective travel distances, visual sickness, and user performances.

In the remainder of this chapter, the author explains the OST and the AWMT method in detail compared to the MT method. Then, the procedures and conditions of a user experiment are described to explore user performance, travel distance, usability, visual fatigue, and preference. Finally, the author discusses the experiment results and presents conclusions.

4.1 Methods to Support Multiple Viewers

4.1.1 Two Users vs. More Than Three Users

Most studies in multi-user interactive visualization compared their interaction techniques by conducting studies with two users and assumed that the results apply to multi-user interaction with more than three users (Blom 2002; Schulze 2012; Tripicchio 2014). To locate the PoV, since two users participated, each user contributed 0.5 to the total mean in the MT scenario. These evaluations showed that the MT method is the best way for multiple users in terms of visual sickness and usability (Tripicchio 2014). This may be acceptable for users because they need to walk only twice farther than the single user tracking method. However, an issue will arise when more users are involved in multi-user visualization. The walking distance will increase proportionally to the number of users; hence the usability may be degraded as the travel distance increases.

The main goal is providing more interactivity and less visual fatigue in VEs supporting multi-user interaction, especially ensuring scalability in terms of a number of users (e.g. supporting with more than two users). To pursue the goal, the thesis proposes the OST and the AWMT method. The OST varies the distance between objects and PoV twice by translating virtual objects towards the opposite direction of the PoV movement, as depicted in Figure 4.1.1. In addition, the AWMT method for active users provides greater weight on active users than stationary users in order to move the PoV. The author assumes that the combination of these two techniques can provide a more effective PoV travel distance for multi-user interaction.

4.1.2 Object Shift Technique

The basic concept of the OST is to shift virtual objects in the opposite direction of the movement of the PoV. In this way, the distance between the PoV and objects is varied and the users' travel distance in the real world can be reduced compared to the MT method. In conventional rendering techniques for multi-user visualization, the PoV is determined based on the users' positions and objects' positions in the VE being fixed unless the users manipulate them. However, using the OST, both the PoV and objects are moving simultaneously in the opposite direction. For example, using conventional rendering techniques, the distance between the PoV and an object is 1 meter if the PoV moves 1 meter. On the other hand, using the OST, the distance between the PoV and an object becomes 2 meters because the object moves 1 meter in the opposite direction of the PoV's movement. Figure 4.1.1 shows a comparison between the conventional rendering and the OST.

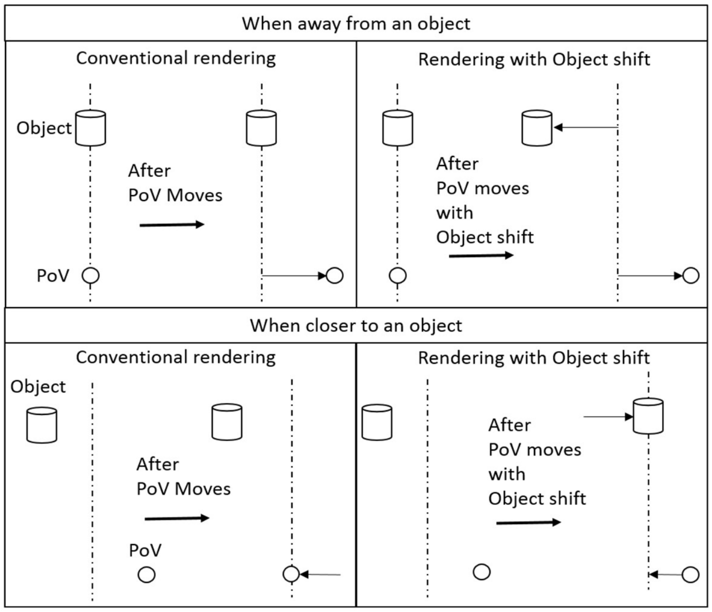


Figure 4.1.1. Comparison between the conventional rendering and rendering with the OST. (When the PoV moves from the object and when PoV approaches to the object)

To apply the OST, the initial positions of objects and the virtual camera are required. When the users move in the VE, the PoV moves corresponding to the users' position. The difference between the initial position and the updated position is calculated, and then the objects are shifted to the opposite side of the direction of PoV movement with the same amount of this difference. Therefore, this technique causes users to perceive as if they are moving twice the distance of how much the PoV moved. The OST is explained more with implementation details in section 4.2.1.

The OST can be applied to any PoV calculation method such as the MT or the AWMT method. The MT method averages users' positions to determine the PoV and the OST doubles the distance between the PoV and objects by shifting the objects in the opposite direction of PoV movement. For example, assume that three users are interacting with a shared large-scale display screen. If only one user moves 1 meter from left to right, the PoV will move only 0.33 meter because of its average movement of all objects. Hence, the moved user may feel the great discrepancy between the actual movement and the rendered movement in VE. This may discourage users from interacting in the interactive visualization. On the other hand, when the OST is applied, the distance between the PoV and objects becomes 0.66 meters by shifting objects from right to left with 0.33 meters (Refer Figure 4.1.1).

The distance between the PoV and a user is related to the level of visual fatigue. In other words, if a user is away from the PoV, the user perceives more visual fatigue than being close to the PoV. The OST shifts only virtual objects and does not translate the PoV. Therefore, the OST varies the travel distance of users while it does not change visual fatigue level.

4.1.3 Activity-based Weighted Mean Tracking Method

In prior work, the MT method has been shown to provide the best usability and visual comfort compared to a number of different approaches for calculating the PoV for multiple users, including fixed tracking, manually switched single tracking, mean tracking, closer-user tracking, weighted mean tracking for closer users and weighted mean tracking with threshold for closer users (Tripicchio 2014). However, this approach may be limited to a two-user scenario rather than with more than two users. As mentioned in section 4.1.2, the usability of the MT method can be decreased with more than two users. The travel distance of the PoV becomes considerably shorter when many users are involved because the weight is evenly distributed across all users. Even if the OST is combined with the MT method, the PoV travel distance is still relatively short.

In this chapter, the author proposes a novel Activity-based Weighted Mean Tracking (AWMT) approach for active users, that provides a higher weight to active users than stationary users. In the AWMT method, the final position of the PoV is calculated based on all of the users’ weighted positions. The active users obtain greater weight than the stationary users. Figure 4.1.2 shows the difference between the MT method that used widely in multi-user visualization and the proposed AWMT method. This approach is based on the assumption that the active users are more interested in interacting with the VE. When the number of users in multi-user visualization is increasing, the tracking method would have the better performance in terms of interaction.

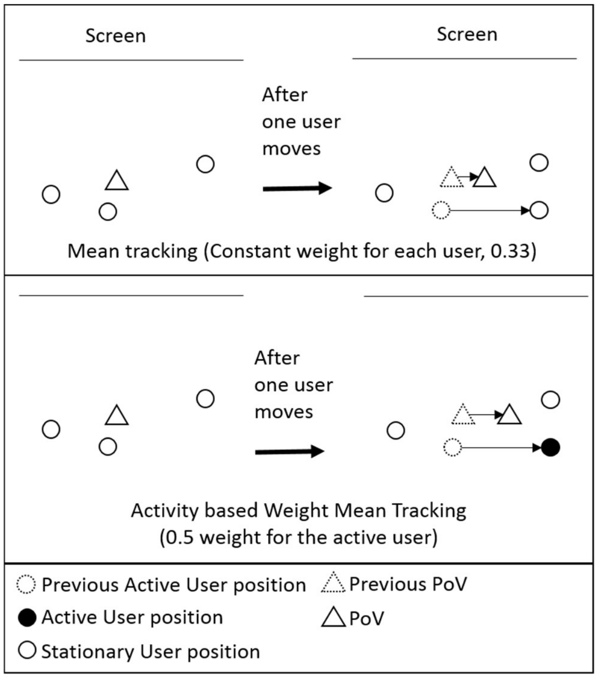


Figure 4.1.2. Comparison between the MT method and the AWMT method.

4.2 Implementation

4.2.1 Object Shift Technique

The OST translates the virtual objects in the opposite direction of movement of the PoV. This technique calculates the position of virtual objects based on the equation (1) where VO and PoV are the positions of virtual objects and the view, respectively. Notation t in subscript denotes the value at the current time, while 0 denotes the initial time value.

$$VO_t = VO_0 + (PoV_0 - PoV_t) \quad (1)$$

For example, assume that the initial PoV is (0, 0, 0), the new PoV is (1, 0, 0) and the location of the initial virtual object is (-2, 0, 0). With the OST, the vector between the initial PoV and the new PoV becomes (-1, 0, 0) and the new location of the virtual object becomes (-3, 0, 0). In this case, the PoV moves only (1, 0, 0) while the virtual object moves (-1, 0, 0). The distance between the PoV and the virtual object changes from 2 to 4 although the travel distance of PoV is only 1.

4.2.2 Activity-based Weighted Mean Tracking Method

Another proposed technique for supporting multiple users is the AWMT method. In the AWMT, the higher weight is assigned to active users in comparison with stationary users. The author limits the maximum weight value as 0.5 to reduce visual sickness since the stationary users could suffer from more visual sickness than the active users. Another reason is that the author assumed the OST enables compensating for the degraded weight. In this section, the author explains more details of the proposed method based on different cases of how the users move.

4.2.2.1 Movement of One Single Active User

According to my definition of the weighting strategy, the weight is assigned as 0.5 to a single user when only one single user moves in VEs. The stationary users share the rest of the weight. In the case of a two-user interaction scenario, the weight is the same for both active and stationary user (0.5) regardless of movement. When three users are participating, the weight for an active user becomes 0.5 and the other two stationary users share the rest of weight (i.e. 0.25 each).

4.2.2.2 Movement of Multiple Active Users

When multiple users travel, the weight values for the stationary users are assigned with the minimum weight (0.1). Then, the active users share the rest of the weight equally. This allows minimizing fatigue for non-active users. For interaction with more than 10 users, the minimum weight should become less than 0.1 as the weight is 0.1 regardless of movement.

4.2.2.3 Transition Between Active Users

When one user moves and stops, and then another user moves sequentially, the weight value changes dramatically. This can generate radical visualization change as well as repetitive jumping objects scene. In a three-user interaction scenario, 0.5 is allocated to the first active user. And then the weight of the second active user becomes 0.5 from 0.25 instantly. This immediately generates a scene discrepancy according to the weight change. To attenuate this issue, a linear interpolation between the weight variation is applied. Therefore, the weight of users gradually increases or decreases to their updated weights as long as they are in the active state.

4.2.2.4 The Best-case Scenario

The method leads to the best result when stationary users are located in the center of the VE and one single active user travels. Figure 4.2.1 illustrates the best case. When the active user moves from A to B, the PoV can move from A to B in the best scenario. In this case, the active user can explore the entire view of the VE without any help from other users. In other words, the closer the stationary users are located in the center of VE, the better the method works for the active user.

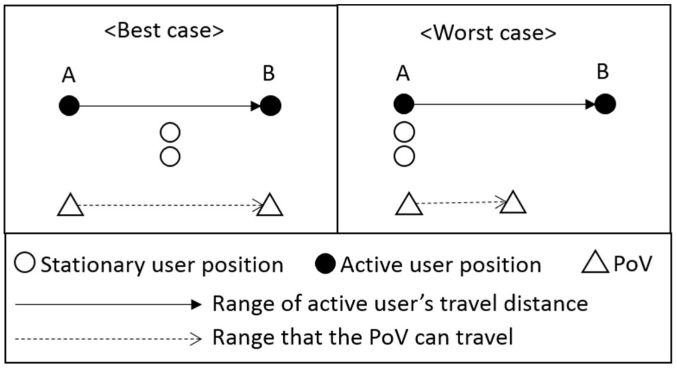


Figure 4.2.1. The best case and the worst case based on stationary users' locations.

4.2.2.5 The Worst-case Scenarios

There are two worst-case scenarios in the AWMT method. The first case is when the stationary users are on one side of the tracking space and only one single active user travels to the other side. In this case, the PoV cannot reach further than the center of VE as shown in Figure 4.2.1. The active user has the weight of 0.5 and the sum of the other is 0.5. Therefore, the PoV stays at the center even if the active user travels to the end of the opposite side of the stationary users. In this worst-case scenario, it is not possible to provide the whole view. Yet, this technique yields a better perspective compared to the MT method. To increase the range of the PoV, the stationary user(s) must move to the center of the tracking space. The second worst case is introduced when two active users move in opposite direction simultaneously. This results in a stationary PoV. This problem also occurs in the MT method. However, this issue rarely happens in multi-user visualization. The author observed that users tend not to move when a user starts to move. The author assumes stationary users try not to disturb the active user.

4.2.3 Combination of the Object Shift Technique and the Activity-based Weighted Mean Tracking Method

The OST varies the distance between the PoV and virtual objects and the

AWMT method allocates higher weight to active users. Based on these two characteristics, the combination of the OST and the AWMT method provides more effective movement for active users than the MT method. With the AWMT method, the weight of one active user can be maximized up to 0.5. In this context, the combination could minimize the visual fatigue similar to the MT method (Tripicchio 2014) based on the distance between the PoV and users. Moreover, the performance becomes more effective in the VEs since the distance between the PoV and virtual objects is varying. Figure 4.2.2 depicts the difference between the MT method and the combined technique proposed.

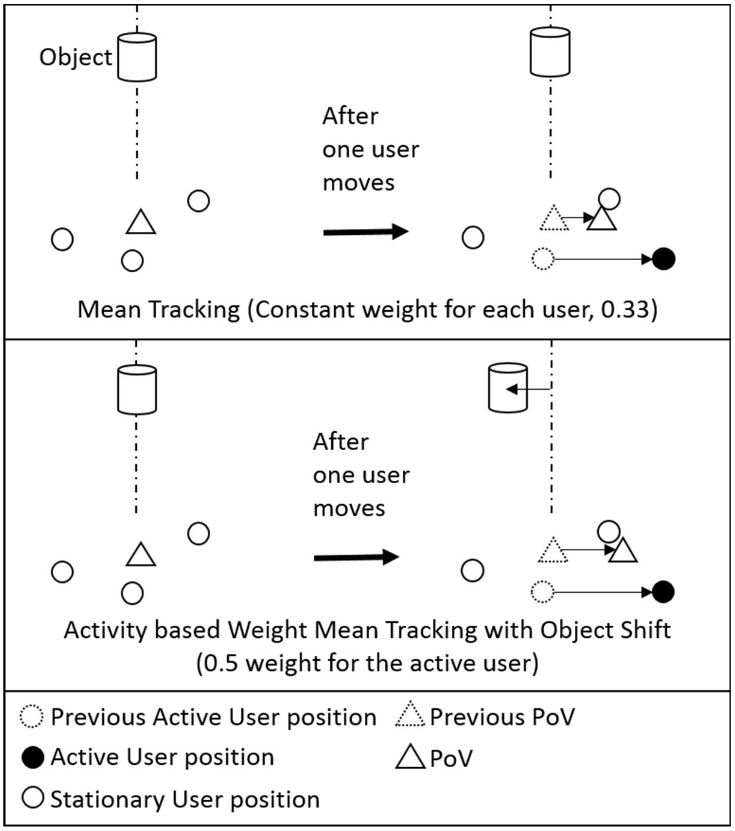


Figure 4.2.2 Comparison between the MT method and the AWMT with the OST.

4.3 Experiment

The author conducted an experiment to evaluate if the OST and the AWMT method can provide a better view, performance, and less visual fatigue than the conventional MT method in a VE. When there is one active user in a VE, the new techniques could perform more effectively than the MT method because they can provide better movement of PoV. The author hypothesizes that the OST and the AWMT will also perform better than the MT method when multiple users are actively moving. Therefore, the user study was designed to compare the OST and the AWMT with the conventional method with multiple active users.

In each experiment session, two real participants participated with one virtual user in order to simulate a three-user interaction scenario. The virtual user was located at the center of the virtual environment and performed as a stationary user throughout the experiment. The other two participants were allowed to travel in order to complete two different tasks per each trial. The author recruited 34 participants (15 males and 19 females) aged 18 to 39 years old (Mean (M) = 27.05, Standard Deviation (SD) = 5.45). All participants had experience with a mobile interface such as smart-phone or a tablet, 61% of the participants had experience with 3D stereoscopic visualization like 3D movies, and 50% of them had experienced virtual environments such as CAVE-like or large-scale display systems.

4.3.1 Experimental Condition

Four different conditions were employed in the experiment as follows:

(1) ME: Mean Tracking method without Object Shift Technique (baseline condition)

(2) MOS: Mean Tracking method with Object Shift Technique

(3) WE: Activity-based Weighted Mean Tracking method without Object Shift Technique

(4) WOS: Activity-based Weighted Mean Tracking method with Object Shift Technique

With the MT method, the final PoV was calculated through the mean vector between the positions of the two participants and one stationary virtual user (See Figure 4.2.3). The weight for the active users was 0.45 and 0.1 for the virtual stationary user in the cases with the AWMT conditions. For the OST, the initial PoV was the center of the VE space.

4.3.2 Experimental Setup and Procedure

The experiment used the *VisionSpace* system mentioned in Chapter 1 and Figure 4.2.3 shows the experimental setup.

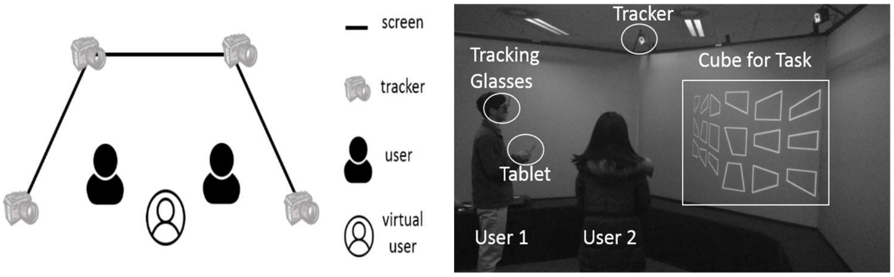


Figure 4.2.3. Top down view of the experiment setup (left) and experiment Setup (right)

At the beginning of each condition, the participants were asked to stand at the center marked on the floor. When the experiment started, a large cube comprising of 3 by 3 images on each surface was displayed on the large display. Each image was a warped or color-filled square as shown in Figure 4.2.4. The warped square images and color-filled square images were placed randomly on the surfaces of the cube in each task. Based on the users' position and the tracking technique, the position and rotation of the cube could be changed. For example, when the PoV moves left, the left side of the cube would be displayed. The right side of the cube would be displayed when the PoV moves right. With OST, the position of the cube would be shifted according to the location of the PoV.

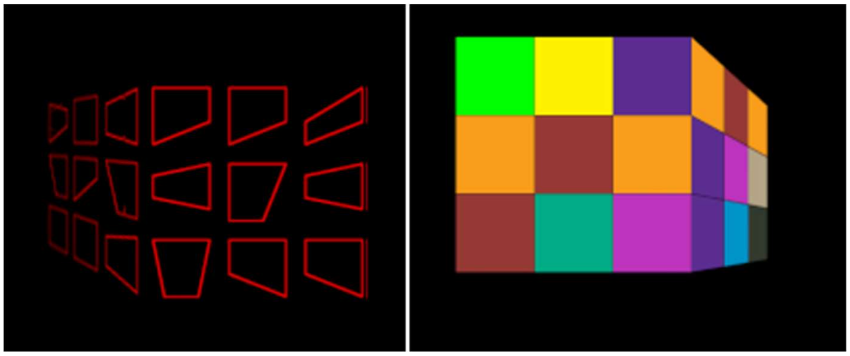


Figure 4.2.4. An example of a cube consisted of 3 by 3 warped square (left) or color-filled square (right) displayed on the large screen.

As shown Figure 4.2.5, the tablet displays the location of the target image in the cube (on the left side) and four answer images (on the right side). The gray squares indicate a planar figure of each side of the cube in the large screen display, which does not include the back surface. The left image in Figure 4.2.5 is the example of warped squares on the cube. The right image in Figure 4.2.5 is the example of color-filled squares on the cube. Additionally, the author marked the location of the cube in the right image (top(T), bottom(B), left(L), right(R), and center(C), please note that these notations were not presented during the experiment).

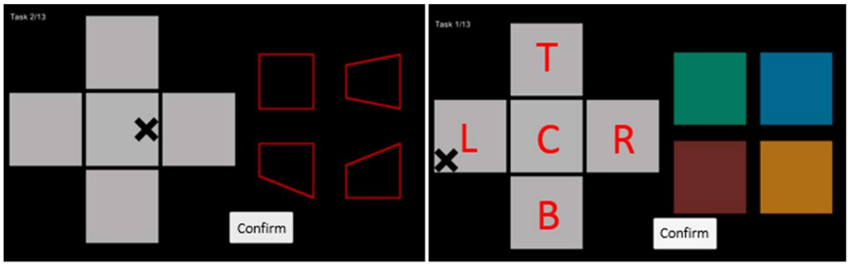
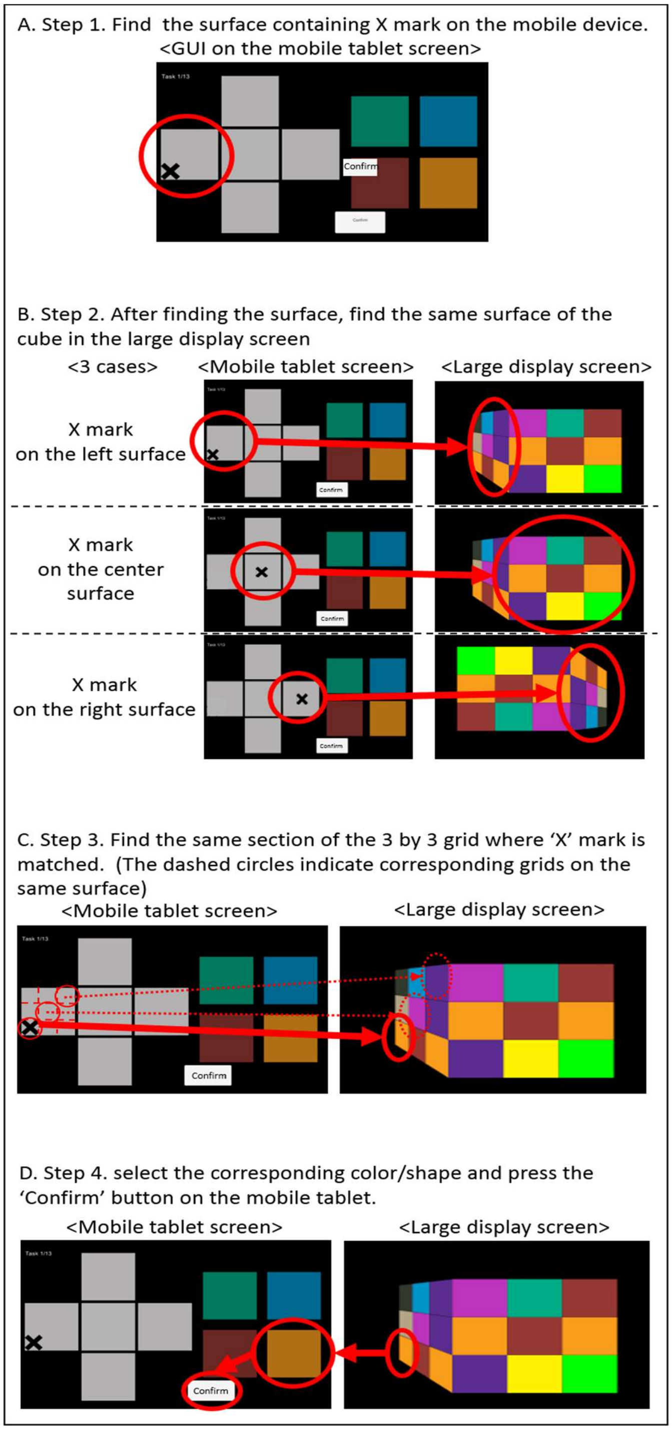


Figure 4.2.5. The graphic user interface on a user's tablet.

The participants can move around in the VE to find the target image in each condition. If the participants find the target image on the large screen and then select the identical shape or color among the four answers displayed on the tablet, one task is completed.

The detailed procedure of the task is explained in Figure 4.2.6. When the experiment started, the screen on each mobile tablet displayed the graphic user interfaces shown in Figure 4.2.5. The participants were asked to find the surface containing the 'X' mark in the planar figure on the mobile tablet (Step 1 in Figure 4.2.6). After identifying the surface, the participants were asked to find the same surface of the cube on the large display screen (Step 2 in Figure 4.2.6). Based on the users' movement, the cube on the large screen showed different sides of it as the user's head is tracked to control the PoV. Therefore, the five visualized surfaces (left, center, right, top, and bottom surface) of the cube could be explored by the user movement. In step 3, the participant was asked to find the same section on the identified surface, divided into a 3 by 3 grid where the 'X' mark was placed. As shown in step 3 in Figure 4.2.6, on the mobile tablet screen the 'X' mark was shown on the left bottom of the left surface. Therefore, the participants needed to find the corresponding location on the cube shown on the large screen display and identify its color, which is orange in this case. The dashed circles indicated corresponding grids on the same surface. To complete the task, the participants needed to select the corresponding color/shape and press the 'Confirm' button on the mobile table screen. This is the process of a single task for the experiment. The participants were asked to repeat the task 12 times for each condition.



A. Step 1. Find the surface containing X mark on the mobile device.

B. Step 2. After finding the surface, find the same surface of the cube in the large display screen

C. Step 3. Find the same section of the 3 by 3 grid where 'X' mark is matched. (The dashed circles indicate corresponding grids on the same surface)

D. Step 4. select the corresponding color/shape and press the 'Confirm' button on the mobile tablet.

Figure 4.2.6. Procedure of the single task including 4 steps in the experiment

Table 4.2-I summarizes the expected users' movement based on target position. The author defined 12 possible user movements that create a natural flow of movement in the tracking space. The experimental tasks in each condition started from one of the four tasks: No 1, No 4, No 7, or No 10. The starting task for each experimental condition (ME, WE, MOS, and WOS) was assigned randomly for counter-balancing. Once a starting task number was selected, the rest of the following tasks were decided as a consecutive task number as shown in Table 4.2-I. For example, when task No 4 was a starting task, the following 12 tasks (No 4, 5, 6, 7, ..., 12, 1, 2, 3) were sequentially conducted by a participant.

Task No 1, 2, 3, 4, 5, and 9 are used to evaluate the proposed techniques in the worst-case scenario mentioned in Section 4.2.2.2 and to investigate how users can solve the worst-case scenarios and how the interaction techniques can support or disturb users in worst-case scenarios. In the tasks, the PoV is fixed when users travel opposite direction simultaneously. However, to complete the task, participants need to discuss with a partner, so that they can travel sequentially or together in the same direction.

Table 4.2-I. The target location on the cube and expected movement for the experimental tasks (L: Left, R: Right, and C: Center)

Task No.	**User 1**		**User 2**	
	Target Position	**Movement**	**Target Position**	**Movement**
1	Left	L ← C	Right	C → R
2	Right	L → C → R	Left	L ← C ← R
3	Center	C ← R	Right	L → C → R
4	Right	C → R	Left	L ← C ← R
5	Center	C ← R	Center	L → C
6	Left	L ← C − R	Left	L ← C
7	Right	L → C → R	Right	L → C → R
8	Center	C ← R	Left	L ← C ← R
9	Left	L ← C	Center	L → C

10	Center	L → C	Right	C → R
11	Left	L ← C	Left	L ← C ← R
12	Center	L → C	Center	L → C

Before each condition, participants practiced the tasks and the four different tracking techniques until they were familiarized. This took about 10 to 15 minutes. The participants were requested to refrain from unnecessary movement for the tasks and to complete the tasks as fast as and as accurate as possible for the experiment.

4.3.3 Measurement

For the objective measurement of the participants' task performance, the author collected the task completion time (*tct*), the percentage of correct answers and the total travel distance. The author also obtained subjective feedback through the questionnaires. After completing each experimental condition, participants were asked to answer a set of 7-point Likert-scale usability rating questions and to complete the System Usability Scale (SUS) (Brooken 1996). To measure 3D stereoscopic fatigue, the participants answered 7-point Likert-scale questionnaires including a level of stress, eyestrain, uncomfortable vision, headache, eye irritation, burning eye, neck pain, pulling feeling of eyes, an ache in or behind eyes and watery eye as suggested in (Lambooiji 2009). In addition, dependency (how much one user tried to help the other) was determined with a 7-point Liker-scale as well. After completing all the experimental conditions, participants were asked to rank the four interaction methods based on their preference and to give comments on their experiences.

A repeated measures two-way ANOVA Test was employed by using SPSS for investigating the influence of different tracking methods and the OST in task completion time, total travel distance, and SUS. A non-parametric

Friedman test was applied in order to analyze preference of four conditions with α level of 0.05 and the Nemenyi test (Hollander 2013) was used for the post-hoc test. In addition, a non-parametric Friedman test was also applied to analyze the other Likert-scale results (correct answer rate, fatigue, depth perception, and dependency) with the α level of 0.05, and post-hoc tests using Wilcoxon signed-rank tests with the Bonferroni correction (Bonferroni, 1936) ($\alpha = 0.008$) was applied.

4.4 Result

In the section, the statistical results of the experiment are discussed. The results showed that the OST could support users to complete the tasks faster. Also, both the OST and the AWMT method could help increasing users' mobility and reducing the travel distance in the VE compared to the MT method. The statistical results of System Usability revealed that the AWMT and the OST could improve the usability of multi-user interaction in the VE. Additionally, the OST could increase the individual user's independency while the AWMT could help the independency slightly. Overall, the participants liked the WOS condition compared to the other condition.

4.4.1 Task Completion Time

Figure 4.4.1 shows the average task completion time (*tct*) for the four experimental conditions. As shown, the WOS provided the shortest task completion time (Mean (M) = 97.06s, and Standard Deviation (SD) = 34.30s) while the ME condition resulted in the longest average duration (M = 119.93s, SD = 37.73s).

A repeated measures two-way ANOVA test revealed that there is no interaction between the tracking method factors and the OST factor ($F(1,16) = 1.031$, $p = 0.327$). There was no main effect of tracking method factor (between the MT method and the AWMT method) in terms of *tct* ($F(1,16) =$

1.240, p = 0.270). However, there was a statistically significant main effect of the OST factor (F (1,16) = 8.041, p = 0.012*[18]).

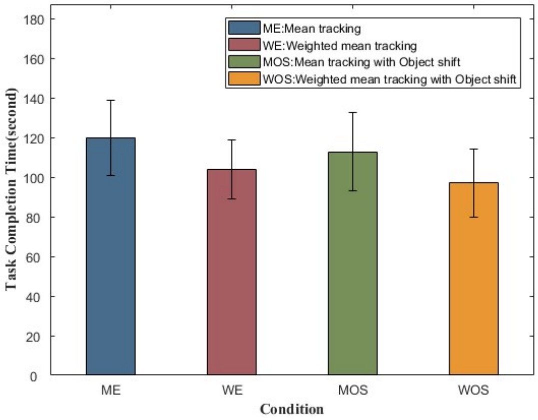


Figure 4.4.1. Task completion time for all conditions. (Bar represents standard deviation)

4.4.2 Total Travel Distance

Figure 4.4.2 shows the average total travel distance of four conditions. There was also no interaction between the two conditions (F (1,16) = 0.360, p = 0.557). Both main effects of the tracking conditions (F (1,16) = 21.065, p < 0.001*) and the OST condition (F (1,16) = 17.193, p = 0.001*) showed significance in total travel distance. Figure 4.4.2 shows total travel distance of four conditions. Analogous to *tct*, the WOS condition (M = 27.75m, SD = 7.97m) had the shortest travel distance whereas ME (M = 39.63m, SD = 8.02m) provided the longest travel distance.

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[18] $*p < 0.05$, $**p < 0.008$

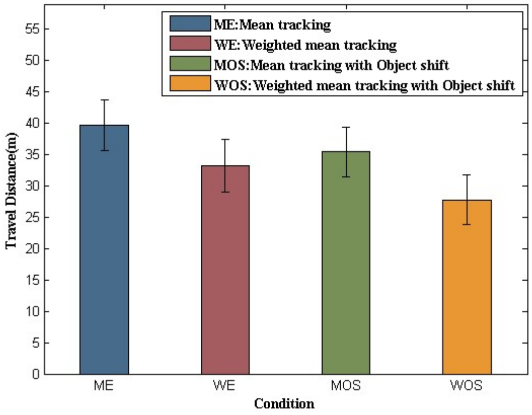

Figure 4.4.2.Total travel distance for all conditions. (Bar represents standard deviation)

4.4.3 System Usability Scale

Figure 4.4.3 shows the System Usability Scale score for the four conditions. Similar to the result of *tct* as well as total travel distance, ME (M = 58.89, SD = 13.69, D grade) was given for the worst SUS score while participants gave WOS (M = 73.01, SD = 6.60, B grade) the highest SUS score. Interaction between the two factors was not significant in the SUS score (F (1,16) = 1.467, p = 0.243). However, there were significant main effects in both the tracking factor (F (1,16) = 6.377, p = 0.023*) and the OST factor (F (1,16) = 41.136, p < 0.001*).

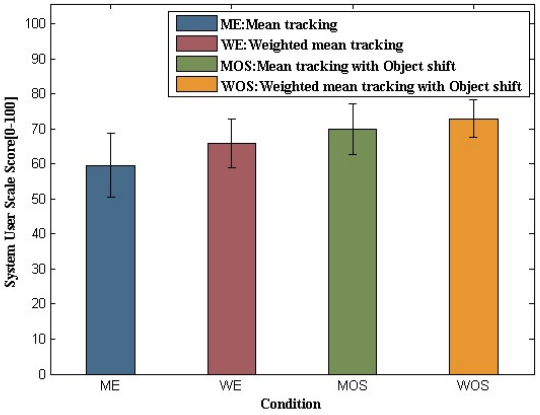

Figure 4.4.3 System Usability Scale for all conditions. (Bar represents standard deviation)

4.4.4 Dependency

The dependency metric shows how much one user tried to support the other user while performing the tasks. A high score of dependency means that users needed more help from their partners. Figure 4.4.4 shows the average dependency score for all conditions. The Friedman test showed a significant difference (X^2 = 16.419, p = 0.001*) and the post-hoc tests revealed significant dependency between ME and MOS (p = 0.006**), ME and WOS (p = 0.003**) and WE and WOS (p = 0.003**). Table 4.4-I shows the detail statistical results of dependency with Friedman and post-doc test.

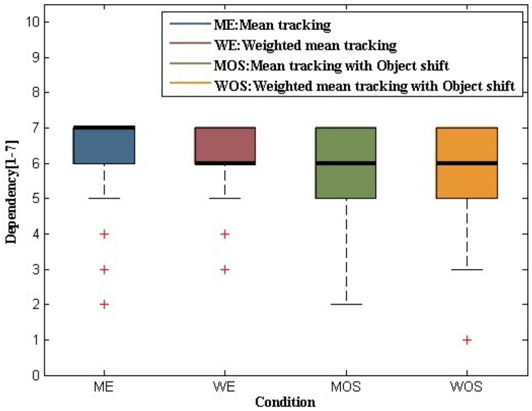

Figure 4.4.4. Dependency for all conditions.

Table 4.4-I. STATISTICAL RESULTS OF DEPENDENCY AND PREFERENCE
(* denotes significant difference)

		Dependency	***Preference***
Friedman Test		$\chi^2 = 16.419$, $p = 0.001$*	$\chi^2 = 44.435$, $p < 0.001$*
Post-doc test results	ME vs WE	Z=-0.243, p=0.808	*p =0.992*
	ME vs MOS	Z=-2.728, p=0.006**	*p < 0.001***
	ME vs WOS	Z=-2.961, p=0.003**	*p < 0.001***
	WE vs MOS	Z=-2.502, p=0.012	*p < 0.001***
	WE vs WOS	Z=-2.996, p=0.003**	*p < 0.001***
	MOS vs WOS	Z=-0.913, p=0.361	*p =0.493*

$^*p < 0.05$, $^{**}p < 0.008$

4.4.5 Correct Answer Rate, Fatigue & Depth

Figure 4.4.5, Figure 4.4.6, and Figure 4.4.7 show the experimental results of the average correct answer rate, fatigue score, and depth perception for four conditions, respectively. The correct answer rate, visual fatigue and depth perception did not show any significant differences. (correct answer rate: $X^2 = 4.395$, $p = 0.222$, fatigue: $X^2 = 2.241$, $p = 0.524$, depth perception: $X^2 = 0.115$, $p = 0.990$).

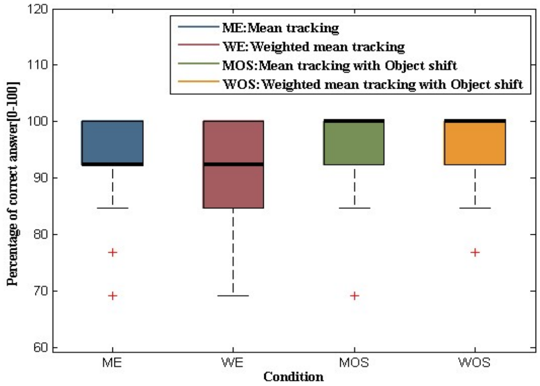

Figure 4.4.5. Percentage of correct answer for all conditions.

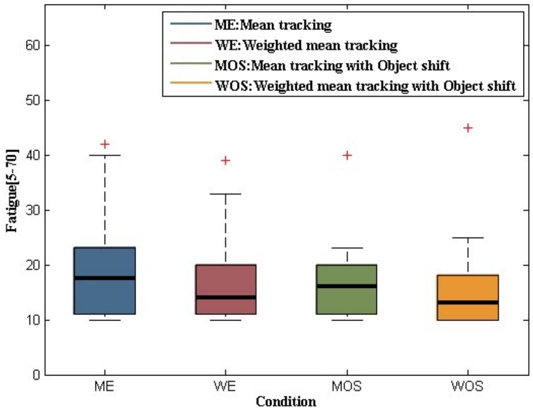

Figure 4.4.6. Fatigue for all conditions.

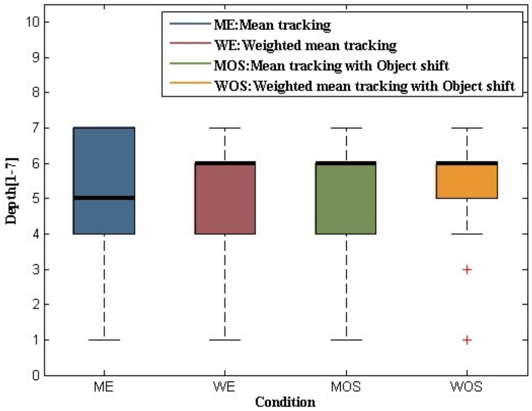

Figure 4.4.7. Depth perception for all conditions.

4.4.6 Preference

Figure 4.4.8 shows the preference response for the four conditions. The Friedman test found a significant difference ($X^2 = 44.435$, $p < 0.001$*). The post-hoc analyses with the Nemenyi test were carried out for all possible pairs and significant differences between ME and MOS ($p < 0.001$**), ME and WOS ($p < 0.001$**), WE and MOS ($p < 0.001$**) and WE and WOS ($p < 0.001$**) were found. In addition, WOS was the most preferred condition among the four conditions. The second preferred condition was MOS (M = 3.029, SD = 0.663). WE and ME followed (ME: M = 1.853, SD = 0.809, WE: M = 1.735, SD = 1.065). The major reason they determined the rank was performance (64.7%) and visual aspects (less distortion or fatigue, 35.3%) was ranked next. The detailed statistical result is shown in Table 4.4-I.

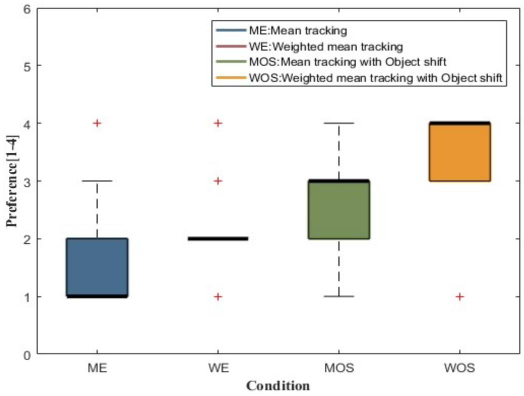

Figure 4.4.8. Preference votes for all conditions. (High score means more preferred)

4.4.7 Qualitative Feedback

I received comments from the participants after the experiment. These can be categorized as follows.

Challenging but enjoyable. Some participants found that matching the same shapes between mobile tablets and the large display was challenging for them. Nevertheless, most participants thought that the experiment was enjoyable. Many participants commented that the 3D visualization experiment was very vivid and interesting. However, some of the rectangular shapes were a bit hard to match together due to their similarities. The participant answered, *“Some rectangular shapes were difficult to distinguish because of the similar shapes and the perspective view”*.

Help from a partner is essential. Most participants agreed with the fact that they needed help from their partners to have a proper view, but the difference between four conditions is the amount of help received from the partner. They answered that the ME condition required more help than the other conditions and MOS and WOS required less support because WOS reflects the participants’ movement more than MOS. One participant commented, *"WOS is the most independent and responsive interaction but it is a bit inconsistent"*.

The Object shift technique is helpful. Most participants responded that the MOS and WOS conditions were easier to have a view from one side to another side compared to the ME and WE conditions. In the MOS and WOS conditions, it was not necessary to move a lot compared to the other conditions (ME and WE). In addition, they did not need to ask their partners to move in some tasks with MOS and WOS conditions.

The Activity-based weighted mean tracking method is inconsistent but could be easily adapted. Some participants noted that the AWMT method is a bit hard to use because of inconsistency. This inconsistency occasionally created an irregular movement of PoV due to the weight variation. For instance, when the participants travel together and one stops, the weight is varying and the PoV moves differently. Despite the occasional inconsistency, they said that they could easily get adapted to the AWMT method. *"The tasks with the WE and WOS were a bit hard to use them at the beginning. However, after finishing the practice session and few tasks, I could get used it."*

No visual differences between all conditions. Interestingly, five participants said that they could not find any visual differences among all conditions, even though the OST was employed. A participant answered, *"I could not find the big difference between conditions, so it was hard to rank them."*. The author thinks that they did not consider the translation movement of the virtual objects and only focused on the cube on the large display. The results of individual travel distance showed that they moved less than their partner, which may allow them to focus on the cube more. They could not recognize the visual difference.

The ME condition is good for collaboration. In terms of collaboration, the ME condition was preferred by a couple of the participants. The comments from the participants were *"I like moving with a partner together."* and *"I liked this interaction because it allows us to work in groups of two and try and figure out how to complete the task at hand."* They did not consider the performance between conditions and focused on the collaboration aspect more.

4.5 Discussion

Based on the results of statistical analysis, the author highlights the differences between the four interaction techniques:

Performance. The OST helps to reduce mean travel distance and task completion time. The author believes that the main reason for this was that the OST translates virtual objects in the opposite direction of the PoV's movement and makes users feel the technique increases their travel distance in VE. This could support users to perform the same tasks more efficiently than using only the weight mean tracking method or the mean tracking method. In addition, the AWMT method could assist reducing travel distance. With only the AWMT method, users could travel less in the physical space than with the conventional MT method. The combination of two interaction techniques enables moving users to see more with less movement. The result of the correct answer rate implies that participants were able to perform the tasks correctly over the four conditions. In other words, the required total travel distance and *tct* were significantly different according to the conditions while still having a similar level of performance. It is interesting to note that some users did not notice visual differences between the conditions even if the results of total travel distance and *tct* were significantly different. The results of individual travel distance showed that they moved less than their partner, which may allow them to focus on the cube more than to notice the translation movement.

Fatigue and Depth perception. With the AWMT method, active users can contribute more weight than stationary users and it may generate another user's visual fatigue because of distorted visualization or depth compression due to the closer PoV for the active users. However, the statistical result showed that there was no significant difference between the MT method and the AWMT method in terms of fatigue level. According to the AWMT strategy defined, users could have weights from 0.25 (stationary) to 0.5 (active), which is similar to the weight of the MT method for the three-user scenario (weight: 0.33). In this context, the participants could have perceived a similar amount of fatigue and a similar level of depth perception in all conditions.

Dependency. The main drawback of the MT method is that users rely on other users to have a different angle of view to complete the tasks. The combination of the AWMT method and the OST could allow the users to have independent movements to complete the same collaborative tasks.

Usability. The result of System Usability Scale(SUS) score shows that the OST and the AWMT method could improve usability. Again, the main reason of the low usability of the ME condition is that users need to travel more than other conditions.

Preference. The majority of participants voted for the AWMT method with the OST as the preferred condition. On the other hand, most participants agreed that the MT method was not efficient for multi-user interactive visualization because it requires more movement and help from others.

Limitations. Although the OST and the AWMT method provided superior performance, it still has several limitations, which can be improved in future work. First, the OST requires a larger virtual environment than a conventional MT method. The OST shifts virtual objects in the opposite direction of the PoV movements, so it requires a virtual environment twice as large compared to its absent condition. Secondly, the AWMT method performs similarly to the MT method in the worst cases as mentioned the worst scenario in section 4.2.2.2. In addition, the methods support 3D movements but only 2D movements (including left-right and back-forth) were evaluated during the experiment. The author assumed vertical movement (up-down) in VE may be the same as 2D movements. However, it might be possible that scene change is more abrupt due to a sudden jumping action, which could influence user experience as well as performance.

4.6 Conclusion

In this chapter, new interaction techniques for supporting interactive visualization in a large immersive screen display were introduced and evaluated compared to conventional methods. The experimental results showed that the new methods efficiently supported collaborative tasks for multi-user scenario with three users. The implemented techniques effectively reduced total travel distance and task completion time. In other words, the actual distance of the user's movement can be also reduced. Furthermore, these techniques support independency of each user's movement in multi-user interaction by updating weights of users according to their level of activity.

Chapter 5

Reducing 3D Visual Fatigue

This chapter explores how to reduce 3D visual fatigue in multi-user interactive visualization with a shared large-scale display. It is necessary to study the topic with multiple users for visual fatigue for 3D multi-user interactive visualization. However, 3D multi-user interactive visualization with a shared view uses a single PoV to render visualization so that it is same as 3D visualization with a single user. Therefore, in this thesis, the author studied and evaluated 3D visual fatigue with a single user.

In Chapter 2, the author introduced the visual fatigue caused by 3D stereoscopy and the visual fatigue reduction techniques by inappropriate disparity. These approaches to reduce visual comfort from inappropriate disparity can be categorized into depth remapping techniques, generating empty depth information, and adjusting camera separation. The depth remapping techniques can decrease visual discomfort by reconstructing disparity map or depth map. However, the techniques also decrease the overall depth perception. Another problem is computational complexity or requiring sequential information to adjust the depth map. In some cases, it does not work with an abrupt movement of the objects. The generating empty depth information approach may be suitable for the physical stereoscopic camera setup. It may not be the optional solution for the real-time virtual environments because it requires more computation. In a virtual environment, the depth information can be easily obtained using a depth buffer as well. The fixed camera separation approach for handheld devices may not give immersive 3D depth perception in general virtual environment due to the short interpupillary distance. The previous research could reduce visual discomfort effectively although they have several limitations. It requires more computation or more information to adjust disparity information, which may not be suitable for a real-time virtual environment. It is also possible to degrade overall depth perception.

In this chapter, the author proposes a method for adaptively and automatically adjust the interpupillary distance (IPD) according to the configuration of the 3D scene, so that the visualization can maintain sufficient stereo effect while reducing visual discomfort. The author demonstrated the adaptive IPD adjustment method with a single user because it employs a single PoV and is the same environment with multi-user interactive visualization with a shared large-scale display.

In the remainder of this chapter, the author explains the IPD in 3D stereoscopy: the fixed IPD and adaptive IPD proposed. Then, the first experiment for adaptive IPD and its results are discussed. The second experiment to evaluate the adaptive IPD by comparing monoscopic visualization and stereoscopic visualization is presented. Finally, the author discusses experimental results and concludes this chapter.

5.1 Interpupillary Distance in 3D stereoscopy

The main cause of visual discomfort by stereoscopic visualization is inappropriate disparity (an extreme or incorrect disparity) between the views shown to the left and right eyes of the user (Ide 2010). Image disparity results from visualizing the 3D scene from two different perspectives corresponding to each of the user's eyes. The two images generated for each eye depends on various factors, such as the interpupillary distance (IPD), convergence, the distance between a viewer and a scene, the scale of a 3D scene, the size of the display screen, intrinsic camera parameters (such as focal length, coordinates of the images, and radial distortion) and extrinsic camera parameters (camera position and the direction of its optical axis). If these factors are not properly adjusted according to the viewing environment and human factors, the resulting stereoscopic image can have extreme or incorrect disparity, causing visual discomfort and unrealistic scenes. Figure 5.1.1 shows an example of stereoscopic visualization with extreme disparity that results in very different images shown to each eye.

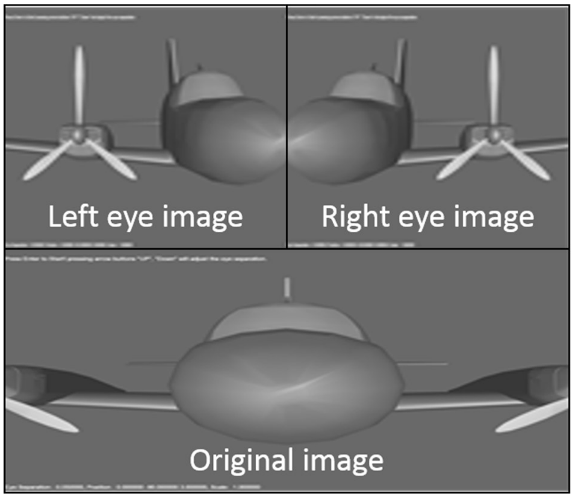

Figure 5.1.1 Stereoscopic visualization with the extreme disparity.

Among the factors, IPD (a.k.a. interpupillary distance or baseline) is the most widely used parameter to adjust the amount of stereoscopic effect (Konrad 1999; Mangait 2012). IPD represents the separation between the two eyes, and it is also used for describing how far the two cameras are displaced to produce stereoscopic images. When the IPD is set to zero, the resulting image shows no stereoscopic effect as the images for each eye become identical. Increasing the IPD gives more depth illusion to the user as the disparity between the two images grows. If the IPD is raised above a certain level, the user starts to feel eye-strain and eventually it becomes hard to see the image correctly (e.g. resulting in double vision).

When visualizing 3D scenes that dynamically change in scale or distance, the IPD needs to be adjusted according to the scene configuration. However, in many cases, it is manually set to a fixed value throughout the content.

Therefore, the IPD has to be adjusted carefully in order to provide sufficient stereo effect while also maintaining user comfort.

5.1.1 Fixed Interpupillary Distance

In the real world, human's eyes converge to create adequate focus and depth perception and the other objects or the background of the object are blurred. This reduces the large disparities between two images for the eyes with fixed IPD when the object is closer to the user. Figure 5.1.2 shows how the eyes can converge to see the far or close object. In virtual reality, the convergence can create another visual discomfort because the scene behind of the object has a large disparity between images for two eyes. This discomfort can be reduced by focusing on the object and blurring the background.

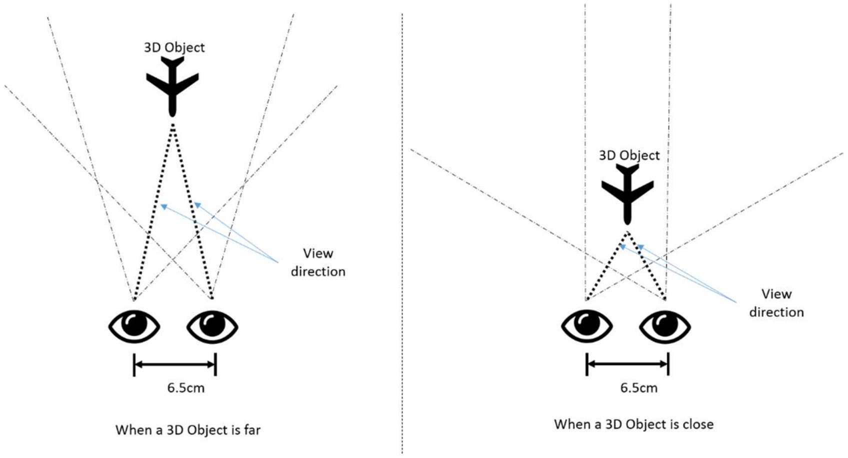

Figure 5.1.2. The difference convergence between the far object and the close object in the real world.

In virtual reality, there are a couple of methods of setting up virtual cameras; toe-in and off-axis.

The toe-in method mimics the human's eye system, but it increases discomfort level in virtual reality (Hodges 1985). Using rotating virtual cameras with fixed IPD to focus on the object is one possible application of the toe-in method. However, this technique still increases visual discomfort because of vertical parallax (See Figure 5.1.3). Also, the blurring technique for reduction of visual discomfort for the method cannot be used in multi-user interaction with a shared large-scale display because the PoV is different from users' locations. Therefore, the off-axis method is widely used to build a virtual environment rather than the toe-in method.

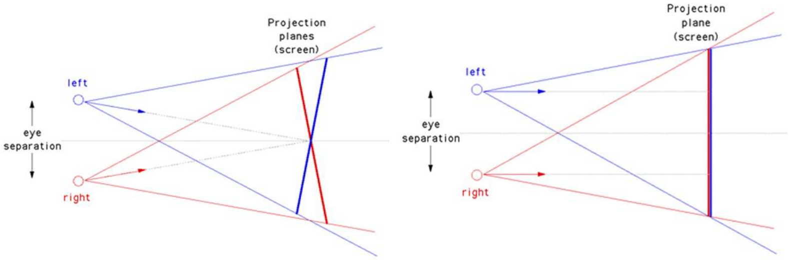

Figure 5.1.3. The difference between the toe-in method (left) and the off-axis method (right).[19]

With the off-axis method, a large disparity can be created when the objects are closer to virtual cameras (PoV) in a virtual environment. The large disparities are produced by the fixed IPD. Because 3D stereoscopic images use the same IPD regardless of the location of 3D objects, this leads to parallax disparities. Figure 5.1.4 describes the typical fixed IPD for 3D stereoscopic interaction system. When the 3D object is at a distance, the disparity between the images is enough to provide depth perception. On the other hands, the disparity between the images became larger when the 3D object is closer to the PoV. A brain cannot fuse the images to create adequate depth perception, which can cause visual discomfort.

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[19] The images are from http://paulbourke.net/stereographics/stereorender/

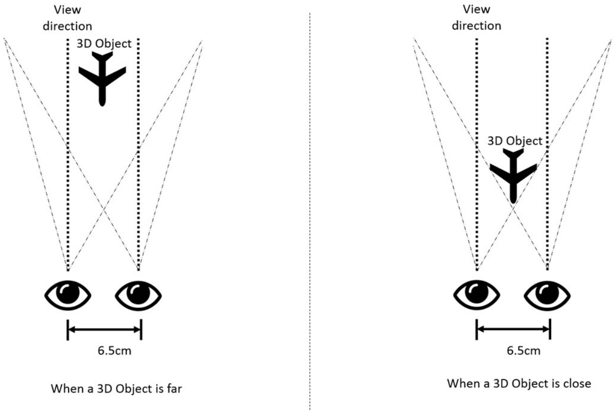

Figure 5.1.4. Typical fixed interpupillary distance in virtual reality.

5.1.2 Adaptive Interpupillary Distance Adjustment

When visualizing 3D scenes that dynamically change in scale or distance, the IPD needs to be adjusted according to the scene configuration. However, in many cases, it is manually set to a fixed value throughout the content as mentioned in the previous section.

Proper IPD for visualizing the stereoscopic images of a 3D scene is decided by many different factors including, physical IPD of the user, the physical size of the screen, and size or distance of the 3D scene relative to the user's viewpoint. Among these factors, the size and distance of the 3D scene relative to user's viewpoint are the factors that can change dynamically depending on the content.

For instance, when a virtual earth is shown from a distance, in order to provide enough depth perception, the IPD should be in the scale of the radius of the earth. On the other hand, when the same virtual earth is shown from the ground level viewpoint (e.g. showing street level view), the IPD should be scaled down accordingly, otherwise, the image disparity will become too extreme causing visual discomfort.

Based on this heuristic observation, the author proposed to automatically adjust the IPD according to the distance between the scene and the user's viewpoint. Figure 5.1.5 illustrates our method to adjust the disparity automatically when the 3D objects in the virtual environment are close or far away.

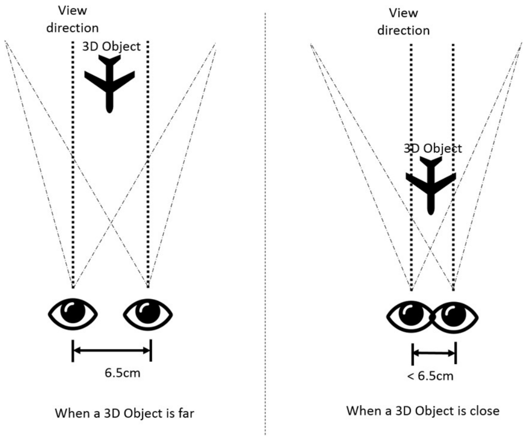

Figure 5.1.5. The interpupillary distance is adjusted when the objects are close to the user.

5.2 Experiment

Two user experiments were conducted to show the feasibility of the proposed method. First, in order to determine the appropriate IPD corresponding to the distance between the user and a 3D scene, the author conducted a user experiment that asked users to choose the proper IPD for varying distance between the scene and the user's viewpoint. Second, the author compared the level of visual discomfort and subjective depth perception between three different visualization configurations: (1) monoscopic visualization, (2) stereoscopic visualization with fixed IPD, and (3) stereoscopic visualization with adaptive IPD.

5.2.1 Experimental Environment

To demonstrate the feasibility of the proposed method, a prototype stereoscopic 3D visualization system was implemented. For displaying 3D stereoscopic images, the experiment employed ‘3D Vision Ready’ active stereoscopic shutter glasses with Samsung 22 inch 120Hz 3D monitor connected to an Intel Core i7 3.4 GHz based computer equipped with Nvidia Geforce GTX670 graphics card. The Open Scene Graph library was used for real-time 3D scene rendering due to its support of quad-buffered stereo. The system allowed the IPD to be adjusted both manually and automatically in order to investigate our method through a user experiment.

Figure 5.2.1 shows the experimental environment. The participants were seated approximately 60cm away from the monitor wearing the active 3D stereo glasses.

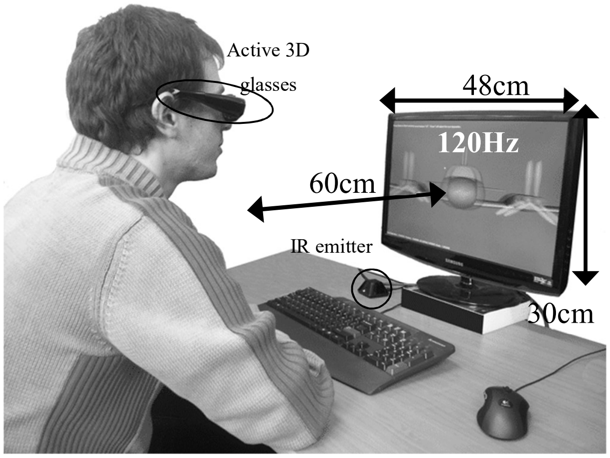

Figure 5.2.1. Experimental Environment

Figure 5.2.2 illustrates the 3D environment used in both of the experiments. Dotted lines represent the view frustum used for the left and right eyes in 3D stereoscopic visualization, and the solid lines show the view frustum used for the monoscopic visualization. For the 3D scene, an airplane model with fairly complex geometries was used. The airplane model was initially located at 100 units (1 unit = approximately 0.5 cm) away from the projection plane and was moved towards the user or further away during the experiment.

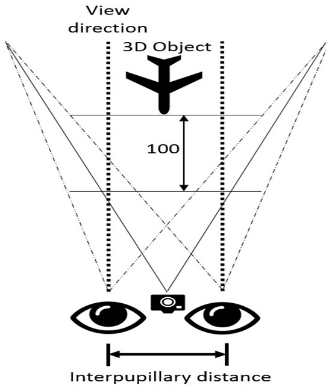

Figure 5.2.2. 3D environment for the experiments

5.2.2 Experiment I

In the first experiment, to measure the appropriate IPD with respect to the location of the 3D object, the author measured IPDs that participants perceived as providing sufficient stereoscopic effect yet comfortable to their eyes.

At the beginning of the experiment, the 3D model was shown at its initial location, and the IPD was set to 6.5 centimeters (cm). The participants were asked to adjust the IPD by pressing the arrow keys on the keyboard to increase or decrease the IPD. They were instructed to find the value where it provided the most depth perception and yet was visually comfortable to their eyes. For safety and to make sure the visualization had minimum stereoscopic disparity, the IPD value to be between 0.1 and 8 cm was restricted.

The experiment continued repeating the same task with the 3D model placed at 9 different levels of distance relative to the initial location of the airplane model (95, 75, 50, 25, 0, -25, -50, -75, and -95 units). The negative values mean the object is placed closer to the user, while the positive values mean it is further away relative to its initial location. While the participant repeated the task from the farthest distance to the nearest, the system recorded the IPD adjusted by the participant for each level of distance. The participants were allowed to take time as much as they needed for eye accommodation at each level of distance and were allowed to take breaks if they felt eyestrain.

5.2.3 Result of Experiment I

12 participants (5 females and 7 males) aged between 25 and 35 years old (Mean (M) = 27.42, Standard Deviation (SD) = 6.31) were recruited. Figure 5.2.3 shows the result of the first experiment with the average value of the IPD chosen by the participants at each level of distance. As shown in the graph, the chosen IPD decreased as the 3D model got closer to the user. When the 3D model was located at -95, which was the closest position in the experiment, the average IPD was approximately 0.4 cm. This result can confirm that as the 3D scene gets closer to the user's viewpoint, the IPD has to be decreased to avoid visual discomfort.

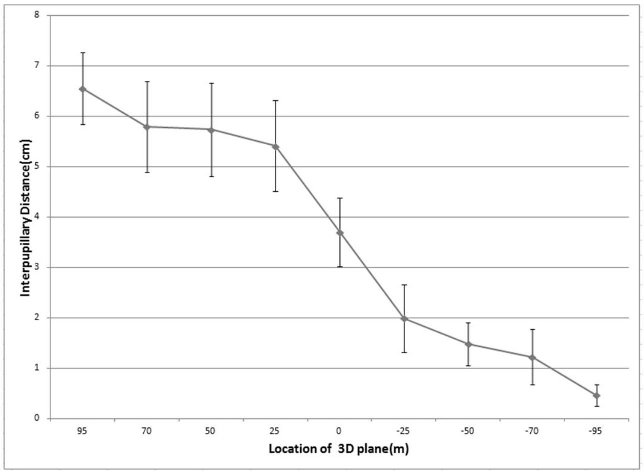

Figure 5.2.3. The result of average interpupillary distance. (Bar represents standard deviation)

5.2.4 Experiment II

The second experiment was conducted to compare our adaptive IPD adjustment method against using a fixed IPD and monoscopic visualization in terms of depth perception and visual discomfort while viewing an animated stereoscopic scene.

A short real-time animation of the airplane flying towards the user was built for the experiment. In the animation, the 3D airplane model moved from -110 to 110 units. The animation was presented to the participant in three different conditions:

(1) MV: monoscopic visualization

(2) SV: stereoscopic visualization with fixed IPD (6.5 cm)

(3) SVA: stereoscopic visualization with adaptive IPD adjustment.

To apply the adaptive IPD adjustment method, the appropriate IPD corresponding to the location of the 3D object was calculated. The experiment used the average value at each distance level calculated from the first experiment and used linear interpolation for the positions in-between (or extrapolation for the points beyond the range). Based on this calculation the IPD was automatically set according to the position of the 3D object as the scene was animated.

The 3D airplane animation lasted for 10 seconds and it was played twice for each condition. After watching the animation under each condition, the participants were asked to answer a questionnaire. For each condition, participants gave a rating using 5-point Likert scale (from 1: strongly disagree to 5: strongly agree) to the four statements:

1) 'I felt like the airplane was moving towards me popping out of the screen.' – Popping-out

2) 'I perceived the 3D depth of the scene.' – 3D depth perception

3) 'I thought that the scene looked natural.' - Naturalness

4) 'I felt eyestrain.' - Discomfort

12 participants (4 females and 8 males) aged between 27 to 36 years old (Mean (M) = 29.36, Standard Deviation (SD) = 5.24) were recruited for the second experiment, and all of them had previous experience with viewing 3D stereoscopic visualization. A non-parametric Friedman test was applied with α level of 0.05 in order to evaluate popping-up rate, 3D depth perception, naturalness, visual discomfort, and preference of three conditions in the second experiment. Also, the Wilcoxon signed-rank tests with the Bonferroni correction (Bonferroni, 1936) ($\alpha = 0.017$) was employed as post-hoc tests.

5.2.5 Result of Experiment II

5.2.5.1 Popping-out score & 3D Depth Perception

Figure 5.2.4 shows the average popping-out scores and 3D depth perception score for the three conditions. The Friedman test found a significant difference ($X^2 = 20.60$, $p < 0.001$*[20]) in popping-out score. The post-hoc analyses with Wilcoxon signed-rank test with the Bonferroni correction were carried out for all possible pairs. Significant differences between MV and SV ($Z = -2.873$, $p = 0.004$**) and MV and SVA ($Z = -3.086$, $p = 0.002$**) were found. There was no difference between SV and SVA ($Z= -2.220$, $p = 0.026$).

In terms of 3D depth perception, a significant difference was found by the Friedman test ($X^2 = 13.412$, $p = 0.001$*). The post-hoc analysis showed that SVA is significantly different from MV ($Z = -2.842$, $p = 0.004$**). The other comparison did not show any difference ($Z = -1.279$, $p = 0.201$ between MV and SV, $Z = -2.220$, $p = 0.026$ between SV vs SVA).

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[20] *$p < 0.05$, **$p < 0.017$

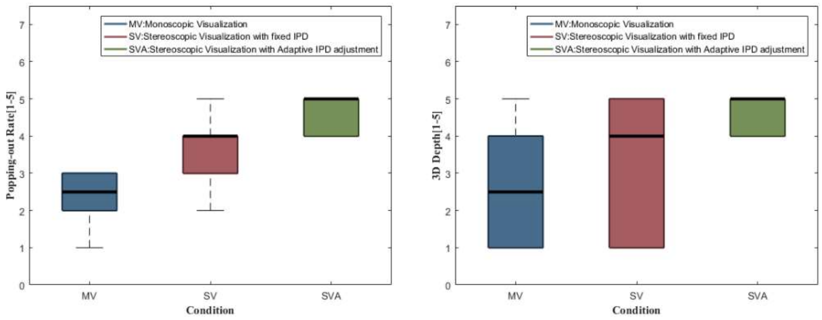

Figure 5.2.4. Popping-out (left) and 3D depth perception (right) for all conditions.

5.2.5.2 Naturalness and Discomfort

The statistical result of the Friedman test for naturalness showed that there was a significant difference between all conditions ($X^2 = 14.000$, $p = 0.001^*$). The post-hoc analysis found significant differences between MV and SV ($Z = -2.640$, $p = 0.008^*$), and between SV and SVA ($Z = -3.162$, $p = 0.002^*$).

For visual discomfort, the monoscopic visualization provided less visual discomfort compared to the other visualization. The statistical result of the Friedman test found there was a significant difference ($X^2 = 17.333$, $p < 0.001^*$) and the post-hoc analysis showed that MV is significantly different from SV and SVA conditions. ($Z = -3.115$, $p = 0.002^{**}$ between MV and SV, $Z = -2.558$, $p = 0.011^{**}$ between MV and SVA)

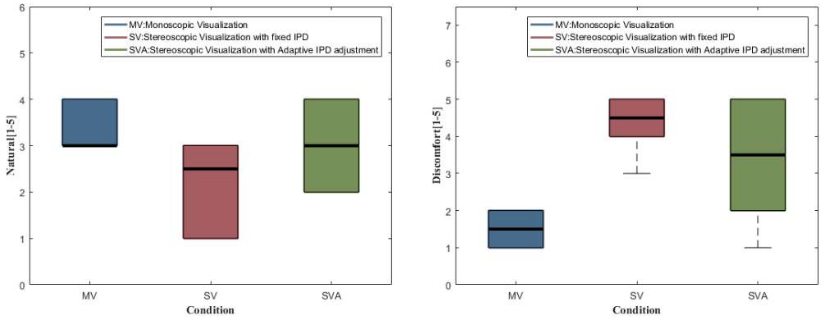

Figure 5.2.5. Naturalness (left) and Discomfort (right) for all conditions.

5.2.5.3 Preference

Figure 5.2.6 illustrates two results of depth perception preference and overall preference. In terms of preference of depth perception, a significant difference was found by the Friedman test. (X^2 = 14.000, p = 0.001*). The post-hoc analysis revealed that there were differences between MV and SV (Z = -2.443, p = 0.015**) and between MV and SVA (Z = -3.145, p = 0.002**).

Overall, SVA was the most preferred visualization among three conditions and SV was the worst visualization. The statistical result with the Friedman test for overall preference showed that there was a significant difference (X^2 = 14.000, p = 0.001*). The post-hoc analysis revealed significant differences between MV and SV (Z = -3.145, p = 0.002**) and between SV and SVA (Z = -2.443, p = 0.015**).

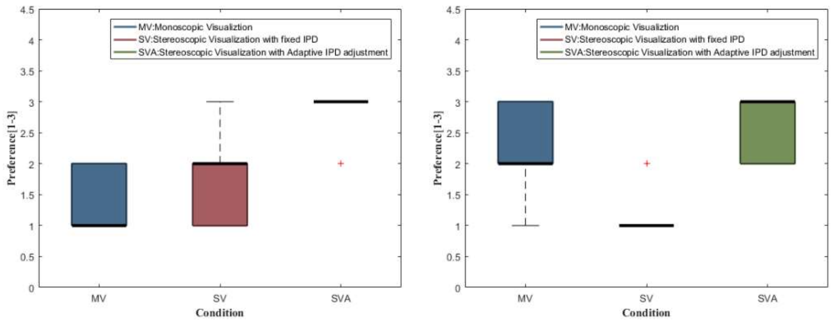

Figure 5.2.6. Depth perception preference (left) and overall preference(right) votes for all conditions. (Higher score means more preferable)

5.3 Discussion

From the result of experiment I, the author found that the IPD needs to be decreased or increased according to the distance between the 3D object and PoV in order to enhance visual comfort level. With the fixed IPD, the stereoscopic images are made with the large disparity when the 3D object is close to the user. This could not provide proper depth perception as well as the sharp shape of the object, which leads visual discomfort. By the narrow IPD, the participants received less depth perception but at least, they could see the 3D object shape.

Based on the result of experiment I, experiment II was conducted to evaluate the adaptive IPD by comparing with conventional 3D rendering techniques. Several observations from the results of experiment II were made.

Depth perception: The adaptive IPD supports depth and popping-out perception. The users can still perceive depth and popping-out without stereoscopic visualization. Monoscopic visualization (MV) cannot create stereoscopic scenes. However, a human can perceive depth from the other cues (motion, relative size, familiar size and so on). These cues enable users to perceive depth perception without stereopsis and to feel the popping-out perception during watching the monoscopic visualization, which was shown the results of popping-out and depth perception of MV.

The author believed that this perception could influence the results of popping-out and depth perception with adaptive IPD. While the 3D object is away from the user, the user can perceive depth perception through 3D stereoscopic images. The depth perception is from the other cues when the 3D object is closer to the user. The narrow IPD is not wide enough to create stereoscopic scenes, however, this could still provide depth and popping-out perception with other cues. Therefore, the adaptive IPD can provide better depth perception compared to the other visualization.

Naturalness & Visual discomfort: The adaptive IPD adjustment can increase the naturalness of 3D stereoscopic visualization and decrease visual discomfort. The results of the naturalness and visual discomfort scores show that the stereoscopic visualization with fixed IPD is more uncomfortable and unnatural. On the other hands, the monoscopic visualization is the most comfortable and natural. The participants commented that they could not view the shape of the object with the animation with 3D stereoscopic technique with fixed IPD when the object is close. With the adaptive IPD adjustment, the participants could see the 3D object regardless of the location of the 3D object. However, they answered that the 3D stereoscopic visualization was unnatural. The result implies large disparity can cause visual discomfort and that visual discomfort can affect naturalness of visualization. The adaptive IPD adjustment method takes two advantages from two techniques. It can provide better visual comfort and naturalness than stereoscopic visualization with fixed IPD.

Preference: The majority of participants voted for stereoscopic visualization with adaptive IPD adjustment as the most preferred condition. The author believes that the participants preferred the adaptive IPD adjustment technique because the adaptive IPD adjustment could provide less disparity and acceptable depth perception. Most participants agreed that the stereoscopic visualization with fixed IPD was unnatural and visually discomfort and did not provide proper depth perception because of the large disparity.

Multi-user Interaction: The adaptive IPD can be adapted to multi-user interaction with a shared large-scale display. Although the experiment was conducted with a single user, multi-user interaction with a shared large-scale display also uses a single PoV like a single user interaction. When users approach the 3D objects, the single PoV will be close to 3D objects. And the scenes rendered with the fixed IPD create the large disparities, which will generate unnatural 3D visualization and depth perception. With the adaptive IPD adjustment, the disparity can be reduced and the visual comfort can be improved for multi-user interaction with a shared large-scale display that employs a single PoV.

5.4 Conclusion

To reduce the visual discomfort in stereoscopic visualization caused by dynamically changed scene configuration, the author proposed and investigated the adaptive IPD adjustment method which automatically adjusts the value based on the distance between the 3D scene and the user's viewpoint. Through two user experiments, the author was able to confirm that the proposed method can reduce visual discomfort, yet maintain compelling depth perception as the result provided the most preferable 3D stereoscopic visualization experience.

Chapter 6

A Framework for 3D Multi-user Interactive Visualization and Its Application to Multi-dimensional Decision-Making VR System

This thesis aims to understand multi-user interactive visualization with a shared large-scale display and to improve the interaction experience. In the previous chapters, the author has explored and demonstrated three topics of multi-user interaction with a shared large-scale display; (1) display setups, (2) interactive visualization, and (3) 3D visual fatigue. In this chapter, the author brings the insights from these techniques acquired from the studies together into a novel software framework for multi-user interaction with a shared large-scale display and describe an example application of the framework to a prototype VR system for multi-dimensional decision-making.

There has been a lot of real-time interactive system application frameworks and many systems in this area support graphics rendering, networking, input, and tracking devices. COTERIE (MacIntyre 1996) provided an environment for distributed systems with objected-oriented data and scene graphs. Using this framework, MacIntyre et al. developed outdoor mobile AR applications with HMDs. DWARF (Bauer 2001) was developed for a platform-independent framework that enables programmers to build AR applications. The services in the framework can be customized by an XML configuration file and can communicate each service. Studierstube (Schmalstieg 2002) was designed with C++ and Open Inventor (Strauss 1992) for collaborative VR and AR environments. This toolkit provided annotations and interactions for a two-handed pen-and-pad input device and a distributed scene graph for networking. Other versions of the framework supported hand-held mobile devices (Wagner 2003) and mobile devices in a backpack (Reitmayr 2001).

MORGAN (Ohlenburg 2004) was a distributed and modular library with C++ for building AR and VR applications. The modules in the library included graphic rendering engine and device abstraction to support various interfaces and the module can also communicate with other modules. GoblinXNA (Oda 2011) and Bespoke (Varcholik 2009) that built on the Microsoft XNA platform[21] supported for integration of external tracking and input systems. These libraries provided a scene graph that could create complex scenes. Similar to these frameworks, ARCS (Didier 2012) developed by Didier et al. supported external module integration. ARCS could extend existing and new-defined modules and define relationships between modules. Using a macro, programmers could create complex modules and integrate them into larger workflows. Figueroa and Castro (Figueroa 2011) developed an abstract and reusable 3D user interface library with C++ and VR Juggler (Bierbaum 2001) that supports 3D graphics

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[21] Microsoft XNA, https://en.wikipedia.org/wiki/Microsoft_XNA

components and an abstract device library for VR applications.

Recently, Unity[22] known as a game engine has become popular in AR and VR fields because it provides an easy interface to build graphic objects and a lot of functionality including supporting earlier libraries and various plug-ins such as supports of HMDs. Elvezio et al. built a software framework named *WF Toolkit* (Elvezio 2017). The toolkit focused on flexibility, which allows to define and implement a modular and interchangeable custom interface for Unity.

Compared to the previous works in the area, this framework not only provides a graphics rendering feature and abstract device layer but also supports 3D stereoscopic visualization and the novel interaction techniques that discussed the former sections. Additionally, this framework supports configuration files to change graphic objects and device setups without recompiling an application as well as additional graphic visualization functions.

Within this framework, the author presents two interactive visualization techniques, (1) the Object Shift Techniques (OST) and (2) the Activity-based Weighted Mean Tracking (AWMT) method. This chapter also discusses a 3D visual fatigue reduction technique and the proposed method for adaptive interpupillary distance (IPD) adjustment. The author defines the active condition for users for multi-user interactive visualization and the proper IPD for the Adaptive InterPupillary Distance adjustment technique (Adaptive IPD). By supporting these interaction techniques and visual fatigue reduction in the framework, their performance and usability can be tested and compared. The insights acquired from investigating the display setups for multiple users are employed to support visualization in the framework. In

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[22] Unity 3D, https://www.unity3d.com

addition, the framework supports head tracking, network communication, and synchronization of multiple devices.

Based on the framework, a prototype VR system for multi-dimensional decision-making was designed and developed. This VR system provides not only multi-user interaction, but also 2D/3D graphs and geometric visualization, and a head-tracked interface.

In this chapter, an overview of the framework is given in Section 6.1, and then the components of the framework are described in Section 6.2. In section 6.3, the prototype VR system is introduced. Then, Section 6.4 discusses the limitations of the framework and the VR system, and lessons learned, and Section 6.5 concludes this chapter.

6.1 Overview of Framework Architecture.

In this section, an overview of the proposed 3D multi-user interactive visualization framework is described. The main design goals of the framework were:

In this section, an overview of the 3D multi-user interactive visualization framework is described. The main design goals of the framework were:

- To provide interactive visualization using the Object Shift Technique and the Activity-based Weighted Mean Tracking methods.
- To reduce 3D visual fatigue for multiple users
- To support various display setups such as a shared view and a split screen.
- To define and support control commands to communicate between the framework and other external devices.

- To support input from multiple control devices and synchronize the between the framework and devices.
- To support additional visualization such as 2D/3D graphs and geometry and visualization layout functions.

Figure 6.1.1 shows an overview of the framework architecture. The framework contains several components to provide various functionality for multi-user interaction. The framework works on multiple threads to ensure the best performance and is based on the following external software components: OpenSceneGraph (graphics), TinyXML[23] (configuration file), OpenSceneGraph Collada[24] and Shapefile[25] Plugins (geometry), Virtual Reality Peripheral Network (VRPN, ART tracking) and Winsock (network)[26].

The remaining sections of this chapter describe each component in more detail and how they work together.

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[23] TinyXml, http://www.grinninglizard.com/tinyxml/

[24] Collada, https://www.collada.org

[25] Shapefile, http://doc.arcgis.com/en/arcgis-online/reference/shapefiles.htm

[26] Winsock, https://msdn.microsoft.com/en-us/library/windows/desktop/ms737523(v=vs.85).aspx

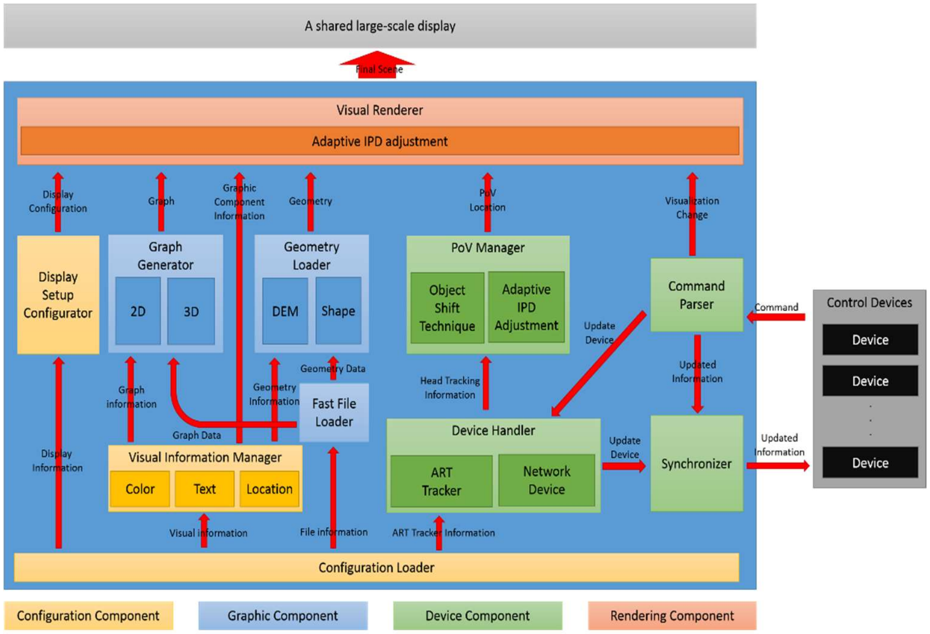

Figure 6.1.1. Overview of the framework architecture.

6.2 Framework Components

In the framework, there are the four main types of components: a configuration component, a graphic object component, a device component, and a rendering component. The configuration component supports the setup of the virtual environment, loading setup information from the pre-defined XML configuration files and initializing the virtual environment for multi-user interaction. The configuration component includes a configuration loader, a display setup configurator, and a visual information manager. The graphic object component generates 2D/3D graphic objects for visualization. The component loads the visual object files such as DEM, shapefile, or customized graphic files and creates visual objects to render them in the virtual environment. The graphic object component consists of a fast file loader, a graph generator, and a geometry loader. The device component manages activities of the devices such as head tracking and input controllers. The component works through network communication and handles commands such as adding a new device and manipulating objects. In addition, the component broadcasts the changes from the system to all connected devices, so that the data in all device can be synchronized. The device component consists of a device handler, a PoV manager, a command parser, and a synchronizer. The rendering component renders all visual objects and updates the rendering scene based on commands. There is only one rendering component in the framework which is a visual renderer. In the following sub-sections, each component is explained in detail.

6.2.1 Configuration Component

6.2.1.1 Configuration Loader

The main function of the configuration loader is to load configuration files before the visual render in the framework renders visual objects such as graphs or a geometry model. The configuration file format is in eXtensible Markup Language (XML)[27] and the detailed schema is predefined based on the requirement of the framework. The configuration loader needs two default configuration files for the framework: (1) the base configuration file and (2) the graphic object configuration file. The configuration files are explained in the section where the files are required in detail. To load XML files, the configuration loader uses the TinyXML library. The loaded configuration is transferred to the components that require the information.

6.2.1.2 Display Setup Configurator

The main function for the display setup configurator is to initiate the display setup for visualizing the virtual environment. The configuration loader loads the display setup from the base configuration file and transfers the loaded information to the display setup configurator to initialize the display setup. The base configuration file describes the number of screens,

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[27] XML, https://www.w3.org/XML/

the size of screens, the resolution of the screens, the location of screens, the initial IPD for 3D stereoscopy, the camera positions for the virtual environment, and the screen type (a shared view and a split screen).

6.2.1.3 Visual Information Manager

The visual information manager extracts the visual information for graphic components such as color, text, and position from the configuration loader. From the extracted information, the visual information manager configures colors, positions, and size of graphs and texts. This visual information manager helps to modify the visual objects without compiling the source code of the framework or the prototype VR system.

6.2.2 Graphic Component

6.2.2.1 Fast File Loader

The fast file loader provides the ability to read graphic files or data files faster than the original file loader included in the OpenSceneGraph library. The default file loader in the OpenSceneGraph library reads files line by line, which is very slow for a large-size file. The fast file loader reads a large-size data file into main memory and then parses it to create the visual objects. This increases the performance of the system. For example, in one test the prototype VR system was reading 130k lines of the geometry data. Without the fast file loader, this took more than 60 seconds. The fast file loader reduces the loading time to less than 3 seconds. After loading files, the fast file loader creates the proper data structures for the graph generator and the geometry generator.

6.2.2.2 Graph Generator

The graph generator creates 2D/3D graphs using the data sets loaded from the fast file loader and the graph information from the graph configuration file loaded by the configuration loader. The graph information contains all the details on how to visualize the graph including the size, the position, the scale, the rotation, the color, the graph guideline size, the axis label, the axis title, the graph title, and the legend.

6.2.2.3 Geometry Generator

The geometry generator creates geometry objects from Digital Elevation Model (DEM) files, Shapefiles, and customized geometry files. The geometry generator also uses the geometry information from the graph configuration file. This component uses the OpenSceneGraph Collada and Shapefile plugins to load the files. The geometry information contains the size, the position, the scale, the rotation, the color of the geometry models.

6.2.3 Device Component

6.2.3.1 Device Handler

The device handler manages to control the input and tracking devices. The device handler accepts connections from new devices and removes disconnected devices via a network. So, any control devices using the correct command packet format can be connected through a network and can communicate with the framework. The device handler maintains the synchronization between devices and the framework by broadcasting updated information to all devices connected to the framework. Since the framework is built using the ART tracking system mentioned in Chapter 1 for head tracking, it mainly supports the ART tracking hardware. The base configuration file has the basic connection configuration information for the ART Tracking hardware. For ART tracking hardware, the VRPN library is utilized.

6.2.3.2 PoV Manager

The PoV manager updates the point of view (PoV) based on the Object Shift Technique (OST) and the Activity-based Weighted Mean Tracking

(AWMT) method. The device handler transfers the head tracking information to the PoV manager. The PoV manager computes the final PoV based on the location of multiple users using OST and AWMT. Then, the computed final PoV information is passed on the visual renderer. Additionally, the manager also tracks which screens the users are looking at if the multiple screen configuration for a shared large-scale display is set up. This information is used to change the user interface on the mobile device in the prototype VR system. This feature will be described in Section 6.3.

6.2.3.3 Command Parser

The command parser analyzes the commands from devices such as adding new devices or manipulating visual objects in a virtual environment. Figure 6.2.1 shows the command packet format sent from the devices. A command packet is divided into multiple parts (fields), and the command parser distinguishes each part using *delimiters*. A *delimiter* is included at the beginning of a packet and between the parts. A command packet consists of 4 parts: length, sender, command, and detail information. The *length* is the total length of the packet in bytes. Using the length, the command parser can separate multiple packets buffered together or merge the fragmented packets. The *sender* identifies the sender device. When a device requests an update or additional information, the framework uses the *sender* part to decide where to return the requested information. For instance, when a new device is connected, the framework returns the name of the device that can be used in the sender field to identify it. The *command* part indicates types of commands such as manipulation, an information request, the type of touch gesture, and a parameter change. The *command* must be defined in the framework to be recognized, otherwise, the framework ignores it. The *detail information* describes optional information to execute the *command*. It can contain the manipulation vector, touch gesture distance, or information for a visualization change such as a color.

Figure 6.2.1. Command packet format.

6.2.3.4 Synchronizer

The synchronizer synchronizes the information between devices. For example, assume that there are two devices (“A” and “B”) connected to the framework. When the device “A” changes the graphs' data, the device “B” also needs to be updated corresponding to the change made by the device “A”. The synchronizer component broadcasts the changes to all devices using the device information from the device handler so that each device can be synchronized with the updated information.

6.2.4 Rendering Component

6.2.4.1 Visual Renderer

The visual renderer takes input from other components in the framework, manages manipulation of visual objects and changes of visualization by the users, and renders the final output. The visual renderer initializes the VR environment using the display setup configuration and virtual objects generated by the graph generator and the geometry loader. When users interact with the VE, the visual renderer draws scenes using the final PoV computed by the PoV manager and the input from control devices. Using the PoV and the position of virtual objects, the visual renderer adjusts the IPD to generate 3D stereoscopic images with less visual fatigue according to the Adaptive IPD technique.

6.3 Prototype VR system for Multi-dimensional Decision Making

The prototype VR system for multi-dimensional decision making was developed based on the framework discussed in the previous section. In this section, the multi-dimensional decision making is introduced briefly and the main features of the prototype VR system are discussed.

6.3.1 Multi-dimensional Decision Making

With the advancement of sensing and simulation technology, the amount of data captured and generated has increased dramatically over the last several decades. Generally, people want to solve certain problems or to make a decision with such massive information. Even though a decision maker can resolve several problems from a huge list of datasets that contains useful information, it is still very difficult to figure out optimal solutions. However, computer graphics visualization methods can be used to assist a decision maker to understand the data more effectively, and intuitively manipulate it.

Multi-dimensional decision making is one method for solving problems when there are many factors involved in deciding the best option. In a design process, identifying all the available solutions and the best one is important for the decision maker. Decision-making processes are usually complex, involving a difficult trade-off between different options. One approach is the so-called "*design by shopping paradigm*", where a set of good solutions are generated and the decision maker can choose an optimal design that meets their preferences (Balling 1999). This gives more control to decision-makers compared to traditional optimization approaches by allowing them to form their design preferences after visualizing the entire design space and then choosing an optimal design.

When multiple objective functions describe an engineering model that has to be optimized, most design optimization problems can be depicted as a Multi-objective Optimization Problems (MOPs). Although designers can find more than one solution for an equation that describes the properties of an engineering model, only a small number of these will be valuable. Thus, the challenge with MOPs is to find out the most useful solution set among all of the found solutions.

One important type of solution set is called the Pareto Set (Pareto 1906), which means

> "*A subset of the set of feasible points of solutions that contain all points that have at least one objective optimized while holding all other objectives constant*"

The Pareto Set is a set of equivalently relevant solutions, and it gives designers additional key information to decide what they want to find. Various methods have been developed for visualizing the Pareto set for two or three objective problems because it can be illustrated in a typical 2D or 3D coordinate system. Figure 6.3.1 shows an example of feasible solutions and Pareto set in 2D coordination.

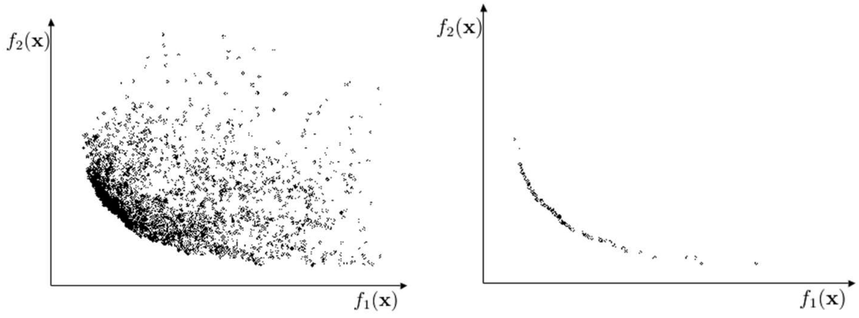


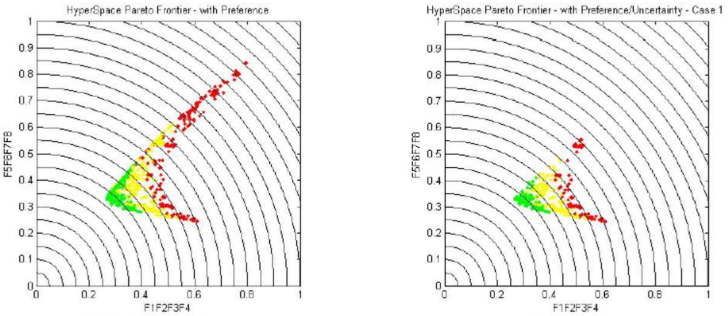
Figure 6.3.1. An example of feasible solutions and Pareto set in 2D coordination.

When more than three objective functions are identified, validation of the solution for MOPs becomes a difficult issue, and it is not easy to represent the Pareto Set. In other words, a simple Pareto surface cannot be produced and a multi-dimensional hyperspace surface must be developed. In this case, the Hyperspace Pareto Frontier (HPF) (Agrawal 2006) refers to the set of optimum Pareto solutions, and several ways have been developed to visualize the data set.

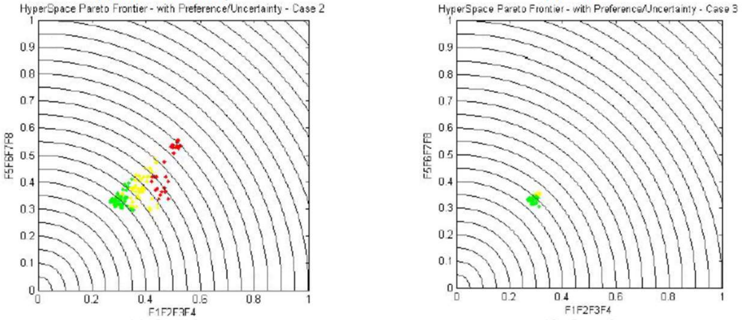
The Hyper Radial Visualization (HRV) Method (Chiu 2009) represents an HPF in an intuitive way for a solution space of any dimension. This visualization method can represent available solutions in a MOP quickly, and it also merges the weighted preferences determined by the decision makers. Moreover, for obtaining more information and responsibility in the decision-making process, an uncertainty representation is used to explain aleatory and epistemic uncertainty corresponding to preference choices after the creation of attributes.

Chikumbo et al. (2012) suggested Approximating a Multi-dimensional Pareto front (AMP). They applied a modified Multi-Objective Evolutionary Algorithm (MOEA) and represented 3-dimensional solutions for 14 objectives. They categorized the 14 objectives into three main issues such as economic (i.e. productivity and financials) and environmental issues, and draw them on the 3D solution space.

For a prototype VR system for the multi-dimensional decision making, the HRV method, the AMP, and additional information such as detail graphs and land geometry are visualized to support multiple users to make a decision based on the decision making by the shopping paradigm is employed. The examples of HRV and AMP are shown in Figure 6.3.3 and Figure 6.3.3. The prototype VR system demonstrates an example of land use management data with 14 objectives, which was used in Chikumbo’s research (Chikumbo 2012).



(a) No Uncertainty **(b) Case 1**



(c) Case 2 **(d) Case 3**

Figure 6.3.2. An example of HRV.

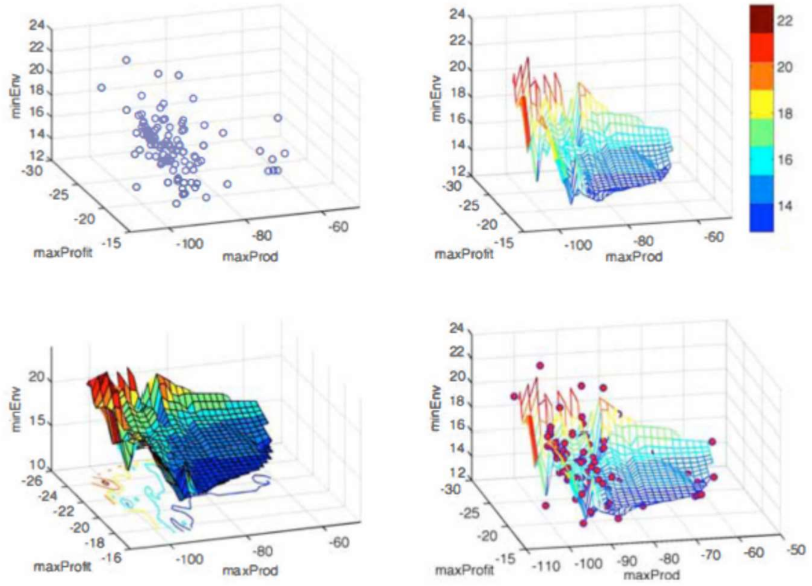


Figure 6.3.3. An example of AMP.

6.3.2 Implementation

The main goals of the prototype VR system for multi-dimensional decision making are as following.

1. Provide an 3D interactive VR system for multiple users.
2. Provide various visualization to aid multi-dimensional decision making in a land use management scenario.
3. Support multiple control devices.

The prototype VR system is demonstrated on the *VisionSpace* immersive visualization facility described shown in Chapter 1. Samsung Nexus 10 tablets are used as control devices and a mobile user interface was built for them with the Unity 3D graphics engine. Figure 6.3.4 illustrates the overview of the prototype VR system.

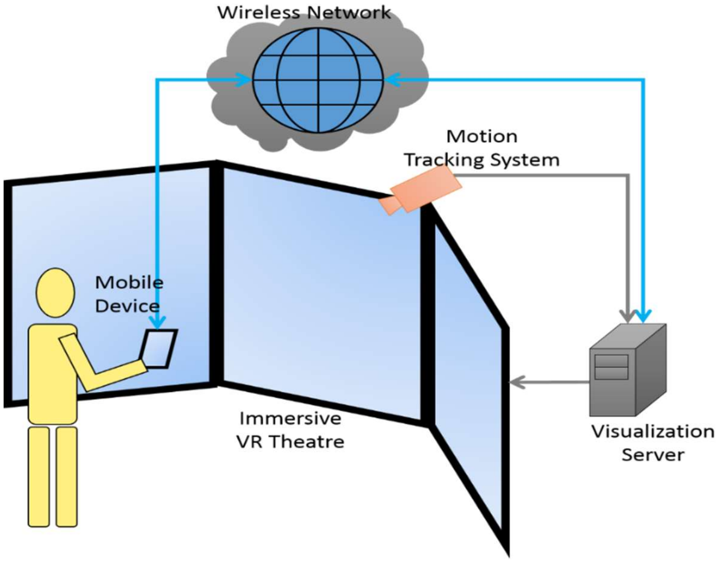
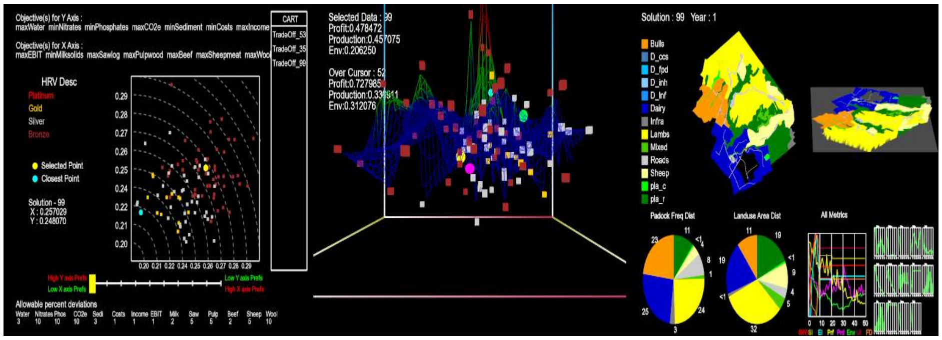


Figure 6.3.4. Overview of the prototype VR system.

Figure 6.3.5 shows a screen capture image of the implementation of the prototype VR system for multi-dimensional decision making. The system visualizes the HRV on the left, the 3D graph for the solutions (AMP) in the middle, and the land usage map and the 2D graphs for each objective on the right. On the left screen, in addition to the HRV, the additional parameters for the HRV are shown and the shopping cart feature is added according to the decision by shopping paradigm. In the middle, the 3D graph for solutions is shown and each axis represents the profit, the production, and the environmental effect for the land use scenario. On the right screen, the 2D map and the 3D Digital Elevation Map (DEM) visualize the land usage over the years of the selected solution with color-coding and legends. In addition, the 2D graphs for the detailed usage are presented.

To interact with the prototype VR system, various user interfaces are required such as changing the parameters for HRV and manipulating the 3D graph for browsing solutions. The system uses a mobile device with a touch screen to provide the user interface for these various interactions. Instead of requiring users to manually switch between different interfaces, the head tracking information is used to display the appropriate user interface on the mobile device. This feature uses the head-tracking function in the framework. For example, when a user faces towards the left screen, the mobile screen shows the graphical user interface that is appropriate for interacting with the left screen.


Objective(s) for Y Axis :
maxWater minNitrates minPhosphates maxCO2e minSediment minCosts maxIncome

Objective(s) for X Axis :
maxEBIT minMilksolids maxSawlog maxPulpwood maxBeef maxSheepmeat maxWool

Solution - 99
X : 0.257029
Y : 0.248070

Allowable percent deviations

Water	Nitrates	Phos	CO2e	Sedi	Costs	Income	EBIT	Milk	Saw	Pulp	Beef	Sheep	Wool
3	10	10	10	3	1	1	1	2	5	5	2	5	10

Selected Data : 99
Profit:0.478472
Production:0.457075
Env:0.206250

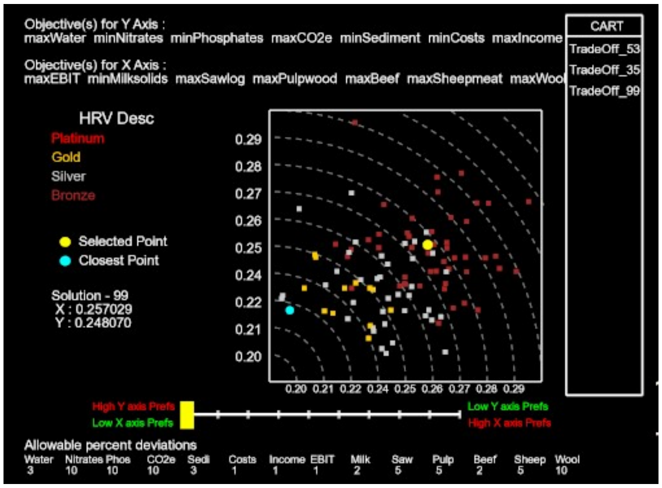
Over Cursor : 52
Profit:0.727985
Production:0.339911
Env:0.312076

Solution : 99 Year : 1

Figure 6.3.5 The prototype VR System.

6.3.2.1 Hyper Radial Visualization

On the left screen of the VR display, the prototype system shows the HRV as shown in Figure 6.3.6. The HRV includes the parameters, the axes, the preferences for the axes, and the deviations. It also includes interfaces to adjust the visualization such as the chosen objectives for each axis (labels at the top) and the predefined preference (the slider at the bottom). The deviation information is shown at the bottom of the screen. The "Cart" interface on the right side shows the trade-off solutions that the users have selected. The users can add, remove, or retrieve the trade-off solutions listed on the cart using the mobile controllers.



Objective(s) for Y Axis :
maxWater minNitrates minPhosphates maxCO2e minSediment minCosts maxIncome

Objective(s) for X Axis :
maxEBIT minMilksolids maxSawlog maxPulpwood maxBeef maxSheepmeat maxWool

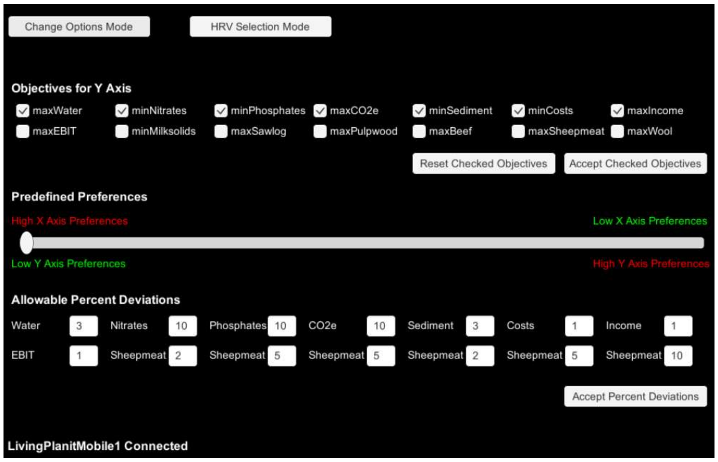
Solution - 99
X : 0.257029
Y : 0.248070

Allowable percent deviations

Water	Nitrates	Phos	CO2e	Sedi	Costs	Income	EBIT	Milk	Saw	Pulp	Beef	Sheep	Wool
3	10	10	10	3	1	1	1	2	5	5	2	5	10

Figure 6.3.6 The Hyper radial visualization in the prototype VR system.

In order to control the HRV, two sets of graphical user interfaces are provided on the mobile device as shown in Figure 6.3.7 and Figure 6.3.8. The HRV parameter control interface enables users to change objectives for each axis, the predefined preference, and the deviations. The HRV selection interface allows users to select a solution in the HRV. The interface also supports to add or remove trade-off solutions on the cart so that they can review the solutions or keep them for further decision making.



Objectives for Y Axis

☑ maxWater ☑ minNitrates ☑ minPhosphates ☑ maxCO2e ☑ minSediment ☑ minCosts ☑ maxIncome
☐ maxEBIT ☐ minMilksolids ☐ maxSawlog ☐ maxPulpwood ☐ maxBeef ☐ maxSheepmeat ☐ maxWool

Predefined Preferences

High X Axis Preferences — Low X Axis Preferences
Low Y Axis Preferences — High Y Axis Preferences

Allowable Percent Deviations

Water 3 Nitrates 10 Phosphates 10 CO2e 10 Sediment 3 Costs 1 Income 1
EBIT 1 Sheepmeat 2 Sheepmeat 5 Sheepmeat 5 Sheepmeat 2 Sheepmeat 5 Sheepmeat 10

LivingPlanitMobile1 Connected

Figure 6.3.7. The HRV parameter control interface on the mobile interface.

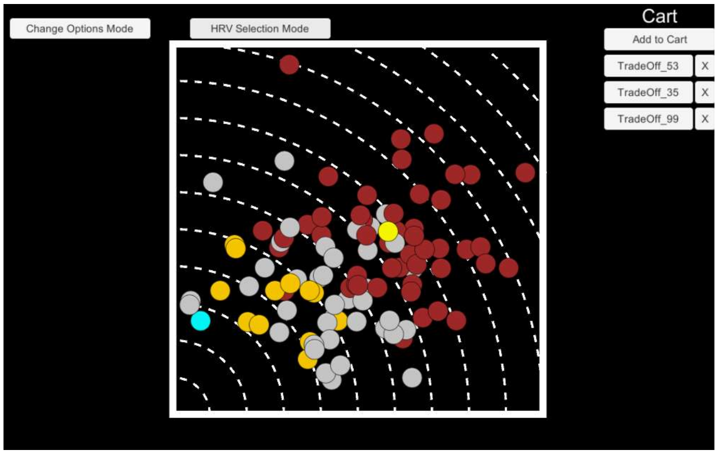
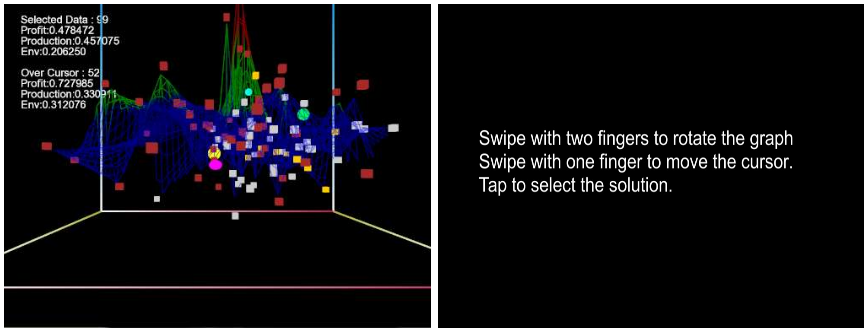


Figure 6.3.8. The HRV selection interface on the mobile interface.

6.3.2.2 3D Graph for Solutions.

Figure 6.3.9 shows the 3D graph of solutions on the VR display and its mobile interface. On the 3D graph of solutions, each axis represents the profit, the production, and the environmental effect. Users can select a solution point using the mobile interface. The mobile interface provides three gesture interactions, one finger swiping, two-finger swiping, and tapping. Users can rotate the 3D graph by using a two-fingered swiping gesture and can move the cursor with a one fingered swiping gesture. After placing the cursor on a solution, the user can select the solution using the tap gesture. When the user selects a solution, the related information such as the HRV on the left and the land usage for the solution on the right are updated on the VR display.



Swipe with two fingers to rotate the graph
Swipe with one finger to move the cursor.
Tap to select the solution.

**Figure 6.3.9 3D graph of the solutions (left)
and its mobile interface (right).**

6.3.2.3 Geometry and graphs visualization

On the right screen of the VR display, the 2D map and 3D DEM with the land use information, and 2D graphs are visualized to show details of the selected solution. Figure 6.3.10 shows the visualized information on the right screen and Figure 6.3.11 illustrates its mobile interface. The 2D map and 3D DEM geometry model visualize the land usage over the years of the selected solution with color-coding. At the bottom of the screen, the frequency distribution and area distribution pie graphs, 2D graphs for the metrics, the line graphs for the 14 objectives data are drawn. Each solution has the 14 objectives data over 50 years and the slider interface on the mobile device is used to browse through the years of the selected solution. The swiping gesture with two fingers is used to change the detailed visualization shown in Figure 6.3.12. To explore the 3D DEM geometry model, the user can rotate it using a one finger swiping gesture.

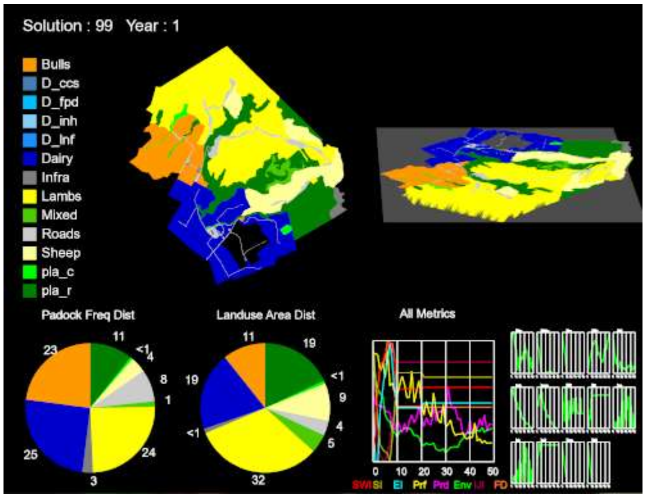
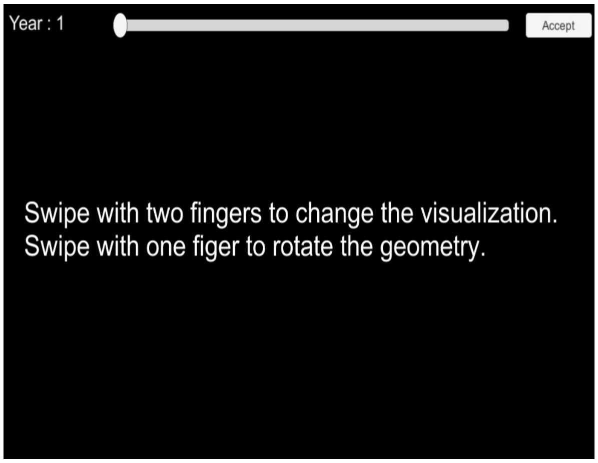


Figure 6.3.10 Land use geometry and graphs visualization.



Swipe with two fingers to change the visualization.
Swipe with one figer to rotate the geometry.

Figure 6.3.11 Mobile interface
for the land use geometry and graph visualization.

The VR system also allows users to zoom into each visualization element. Figure 6.3.12 shows each visualization elements zoomed in from Figure 6.3.10. The 2D map (left-top) and 3D DEM geometry model (right-top) with color-coding are shown in Figure 6.3.12. The "*Paddock Freq Dist*" pie graph shows the frequency of the paddocks distribution and the "*Landuse Area Dist*" pie graph describes the area of the land use distribution. The metrics graph at the middle-right shows the results of the special analysis over 50 years including Shannon-Weiner Index (SWI), Simpson's Index (SI), Evenness Index (EI), Profitability (Prf), Productivity (Prd), Environmental Impact (Env), IJI, and Fractal Dimension (FD). The line graphs at the bottom illustrate the original data of 14 objectives over 50 years.

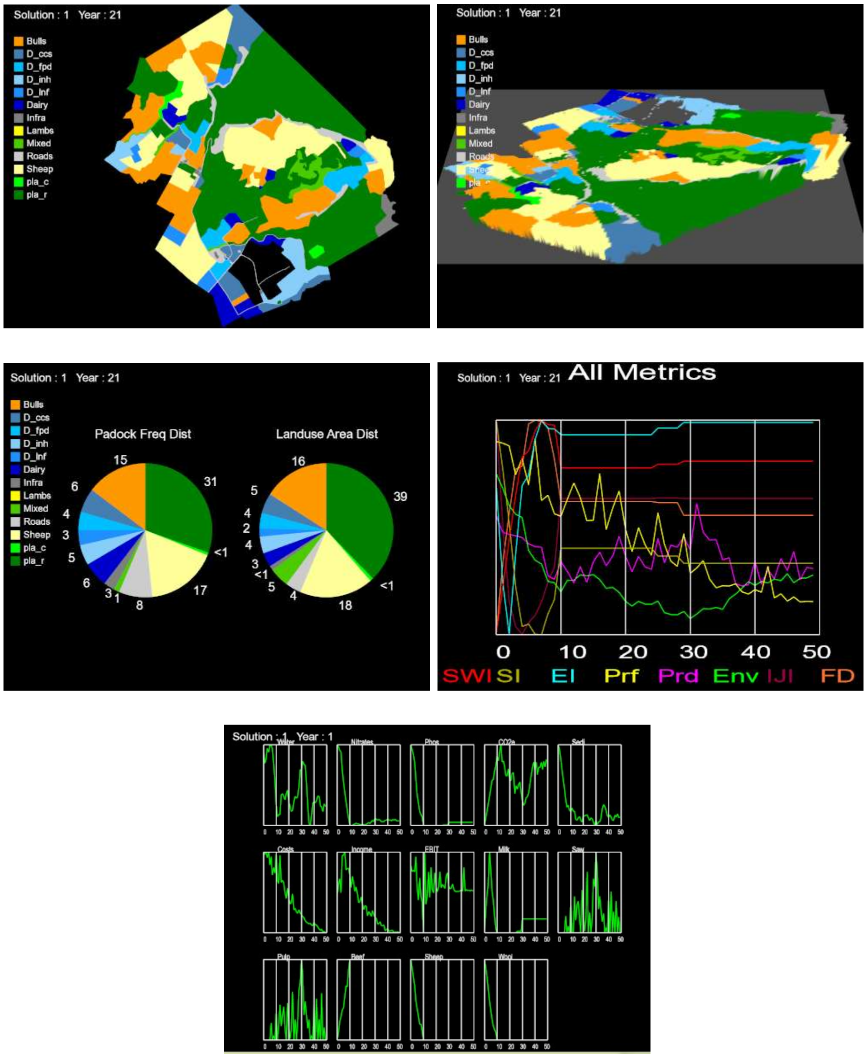


Figure 6.3.12 The 2D land usage map (left-top), 3D DEM geometry model with the land use (right-top), distribution pie graphs (middle-left), line graphs for metrics (middle-right), and line graphs for 14 objectives (bottom).

6.3.2.4 Synchronization between devices

The framework supports multiple mobile devices to allow multiple users to connect and to interact with the VR system. When a user interacts with the VR system, the updated information such as changing the HRV parameters, selecting the solution, and the cart information is broadcasted to the other users through a wireless network. Figure 6.3.13 shows the communication diagram between mobile devices and the VR system.

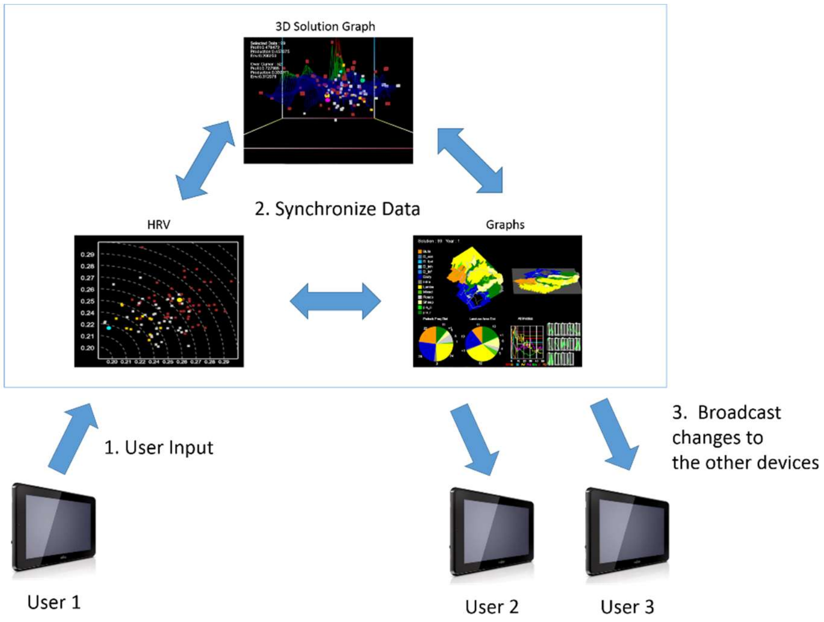


Figure 6.3.13 Communication diagram between mobile devices and the VR system based on user input

6.3.3 Performance

Despite a large amount of data processed and visualized in real-time, the prototype VR system can provide 3D interactive visualization with an update rate of over 20 frames per second (FPS). The system was demonstrated to a group of users, and it was found that experienced users could easily interact with the system such as update the parameters for visualization and rotating the 3D graph and geometry.

6.4 Discussion

In this section, the lessons learned from the design and the development of the framework and the prototype VR system are discussed, and the limitations of the current system.

6.4.1 Summary of the framework

The framework was designed to encapsulate the core components of the display setup for multiple users as described in Chapter 3, the interactive visualization techniques investigated in Chapter 4, and the visual fatigue reduction technique explained in Chapter 5. With the insights from multi-user interaction display setups, the framework can support various display setups for multiple users. Using the OST and AWMT methods, the PoV for VR rendering is adjusted based on the users' movement. And together with the OST and AWMT, the framework can further reduce 3D visual fatigue using the adaptive IPD technique. Network communication and synchronization features are provided in order to support multiple devices. For virtual object visualization, the fast file loader, the 2D and 3D graph generator, and the geometry loader were developed to provide more functions and to enhance the framework. The successful implementation of the framework based on these components helped in implementing the user studies described in this thesis.

6.4.2 Lessons learned from the design and the development

A number of lessons were learned during the design and development of the framework and the prototype VR system. These are summarized in this

6.4.2.1 Trial and error in an active condition of users for interactive visualization.

During the design and the development of the prototype VR system, a trial and error method was used to determine the best parameters for an active condition for users in the AWMT method as described in chapter 4. This was a tedious and time-consuming process, however, it was beneficial for developing the user studies and for demonstrating the VR system.

6.4.2.2 Solving framerate difference.

The buffering of command packets was the most challenging problem in building the framework and prototype VR system. The buffering problem is caused by a different rendering framerate between the framework and control devices and it leads the packet loss. To minimize the packet loss, many practical development techniques such as multi-threading synchronization, and merging and splitting packets are employed.

6.4.2.3 Device Simulator development

To test and debug the framework and the prototype VR system, many devices and tracking information are necessary. During the development, it was hard to recruit three users at once as well as ask them to travel in the virtual environment based on scenarios to tune the interaction techniques. So, a device simulator was developed to simulate the movement of multiple users. The device simulator uses the network communication protocol as described in section 6.2.3.3 and sends command packets to simulate users' movement. It was beneficial to develop a device and tracking simulator for simulating multiple users instead of recruiting users.

6.4.3 Limitation of the framework.

The framework provides the interaction techniques that the author proposed with several base 2D/3D graphs and geometry model features, and network communication to support various devices by defining the protocol for communication. Although the framework could support many functions to build multi-user interactive visualization VR systems, there are still limitations. First, the framework requires manual process in setting up displays to build a VR system. The framework includes the display setup configurator to simplify building VR systems. However, it still requires manual configuration for the displays because the framework cannot know how the physical environment is setup. Second, the different framerates between the framework and devices cause loss of the command packets. When the framerate of the framework is slower than the control mobile devices, the framework can accumulate the command packets. Also, the control mobile sends buffered packets. This occasionally results in missing the command packets. The framework tries not to ignore the command packets as much as possible. However, packet loss can occur, which may require users to perform input again. This problem was partially solved by matching the framerate between the framework and the control devices, and additional processes. However, it did not work completely in all occasions.

6.4.4 Limitation of the prototype VR system

The prototype VR system is built to support multi-dimensional decision making. As there were various types of data visualized, the system showed a mixture of 2D and 3D visual objects together in the same environment, which might cause visual fatigue. The system was designed at least not mix 2D and 3D objects in the same screen, however, it is still possible to see both types of objects at once. A pilot study was held with the small number of users to test this issue and the participants were asked to change the parameters for the HRV, to manipulate 3D graph for solutions, and to interact with graphs on the right screen. The participants answered that they did not feel severe fatigue from the mixed virtual objects as the display screens were separated and big enough that users mainly focus on a single screen rather than watching multiple screens with different types of objects. However, further investigation is required as there are possibilities of having visual fatigue from viewing a mixture of 2D and 3D visualizations

6.5 Conclusions

This chapter described the design and the development of a software framework for multi-user interactive visualization and a prototype VR system using the framework. The framework was implemented to provide a 3D multi-user interactive visualization with a large-scale display implementing interactive visualization techniques using the OST and AWMT methods, and 3D visual fatigue reduction technique using adaptive IPD adjustment. To support building of virtual environments, the framework included network communication, synchronization, and geometry model loading features. The features for each component were explained and the performance and the limitations of the framework were discussed.

To show the utility of the framework, a prototype VR system for multi-dimensional decision making was developed and demonstrated using the framework. The VR system provided a number of visualization of multi-dimensional solution space and the decision making by the shopping paradigms to support the group decision-making process in land use application.

Chapter 7

Discussion

Chapter 1 introduced the topic of this thesis and proposed a number of goals. The work presented in the following chapters focused on display setups for multiple users (Chapter 3), interactive visualization with a shared large-scale display (Chapters 4), reducing 3D visual fatigue (Chapter 5), and the design and development of a framework for multi-user interaction and creating a prototype VR system using the framework (Chapter 6).

This chapter summarizes and discusses the results of each study for 3D multi-user interactive visualization with a shared large-scale display and also reviews the limitations of the thesis.

7.1 Display Setups with a Shared Large-scale Display for Multiple Users

In Chapter 3, the author investigated display setups for multiple users with a shared large-scale display. A shared view and a split screen display setup are often used for multi-user interaction because these display setups are more suitable for information sharing, discussion, and collaboration. Previous research in the field mostly employed a shared view that lets users share the whole space together. However, they did not explore display setups in detail. Therefore, a detailed evaluation for display setups for multi-user interaction with a shared large-scale display was conducted in order to investigate the effect of display setup and the relationship between display setups and multi-user interaction. For this, shared view and split screen display setups were designed and demonstrated. In addition to the two display setups, a third display setup was investigated which added navigation information to the split screen, which is the commonly used concept in VR visualization to provide an overview of the environment.

According to the results of the user study, the split screen with navigation information is preferred over the shared view or the split screen display setup. Most participants voted that the shared view was the worst display setup because of the physical bottleneck of sharing a single controller. Participants said that they felt more confident when they had more information, such as their partner’s viewpoint and navigation information. The two main reasons for the user preference were independency and performance. From these results and the users’ feedback, the split screen display setup and navigation information could increase the users’ confidence level.

The experimental results also showed that the shared view increased collaboration performance. The participants had fewer misunderstandings such as pointing in the wrong direction because they could search matching shapes and discuss it on single visualization view. With the split view with navigation information, the participants spent more time understanding their partner’s view and the navigation information, but the navigation information (NI) helped to reduce the task completion time and touch distance. So, overall there was no significant different performance between the two split view conditions, with the NI and without the NI. With the NI, participants could choose more efficient navigational route hence needing less touch interaction, yet they could lose attention and take more time to understand additional information such as their partner’s view and navigation information.

The results of the usability test (SUS) for the display setups showed that the display setups did not have an impact on the usability. Compared to previous work that found a significant effect, the author postulated that providing controllers to each user could have led to the different result. Providing each user with individual control devices could have increased usability although they could not interact with the system at the same time.

According to the results of the NASA-TLX, the users had more mental demand and more frustration when they collaborated using the shared view. While the NI also increased mental demands slightly, its effect was not significant. With both the split screen and navigation information reduced frustration while each single component did not reduce frustration level significantly. Compared to the previous research, the author suggested that provision of individual devices in the shared view may have increased users' confidence level and collaborative usability.

From these results, there are several insights that can be made about the display setup with a shared large-scale display for multiple users:

- A split screen increases independency although users can lose attention and can spend more time with it.
- A shared view can provide effective interaction and collaboration.
- Navigation information can increase the user's confidence level.
- Having both a split screen and navigation information together can influence the frustration level.
- Display setups may not influence the usability and workload.

7.2 Interactive visualization for multiple users

Chapter 4 explored the limitations of one conventional interactive visualization technique, the Mean Tracking (MT) method. With the MT method, the graphic visualization cannot accurately reflect the users' movement in the VE because the PoV used in the visualization is calculated using the average of multiple users' locations, making the movement of the PoV less than the physical distance traveled. Therefore, in applications requiring frequent movements, such as spatial exploration, the MT method may not be the best solution.

For more interactive visualization for multiple users, the author proposed the Object Shift Technique (OST) and the Activity-based Weighted Mean Tracking (AWMT) method. The OST reduces the user’s physical travel distance by translating virtual objects corresponding to PoV movement. The AWMT method gives higher weights to active users than stationary users when calculating the location of the PoV. The OST and the AWMT are designed to improve the user’s mobility in multi-user VEs without increasing visual fatigue.

The experimental results found that the OST reduced the mean travel distance and the task completion time. The OST translates virtual objects in the opposite direction of the PoV’s movement and so makes users feel their travel distance is increasing in the VE. This supported users to perform the same tasks more efficiently. The AWMT method also helped reducing travel distance because active users had higher weights than stationary users to move the PoV. The AWMT method could provide a similar amount of fatigue and a similar level of depth perception as the MT method. According to the design of the AWMT method, users could have weights similar to the weight of the MT method. Therefore, their visual perception of the VE is also similar to that with the MT method

The combination of AWMT method and the OST enables moving users to see more virtual motion with less physical movement. In addition, it allows users to have independent movements to complete the same collaborative tasks with improved usability. Therefore, the majority of participants preferred the condition with both the AWMT method and the OST in the user study.

From the results of the second user study, the author concluded that the

OST and the AWMT methods can provide effective interactive visualization and give a better experience for multiple users.

7.3 Reducing 3D Visual Fatigue

In Chapter 5, the author discussed one of the main causes of visual fatigue in 3D stereoscopy, the large disparity between the two images for each eye. Previous research has shown how to reduce this visual discomfort although they required more computation or more information to adjust the disparity information, which may not be suitable for a real-time virtual environment. It also may degrade overall depth perception. Therefore, the author developed a simple 3D visual fatigue reduction technique, named "Adaptive Inter-Pupillary Distance (Adaptive IPD) adjustment", that can provide an acceptable result in real-time for interactive virtual reality application.

In order to determine the appropriate IPD corresponding to the distance between the user and a 3D scene, the author conducted a user experiment to choose the proper IPD at varying distances between the scene and the user's viewpoint. The results found that the IPD needs to be decreased or increased according to the distance between the 3D object and the PoV in order to enhance the visual comfort level. The fixed IPD could not provide proper depth perception as keep the virtual object in sharp focus, which leads to visual discomfort. With a narrow IPD, the participants perceived less depth but at least they could see the shape of a 3D object properly. In a follow-up experiment, the author evaluated visual discomfort and subjective depth perception between three different visualization configurations: (1) monoscopic visualization, (2) stereoscopic visualization with fixed IPD, and (3) stereoscopic visualization with adaptive IPD. From the evaluation and the participants' feedback, several observations were made.

According to the results, the author found that the adaptive IPD could support depth and popping-out perception. A human can perceive depth from the various cues (motion, relative size, familiar size and so on) and these cues enable users to perceive depth without stereopsis and to feel the popping-out perception while watching the monoscopic visualization. With the adaptive IPD adjustment method, the user could perceive depth through 3D stereoscopic images when the 3D object is far enough from the user. When it becomes too close to retain normal IPD, the user can perceive depth is from other cues. The adaptive IPD adjustment could also increase the naturalness of 3D stereoscopic visualization and decrease visual discomfort. With the fixed IPD, users cannot properly see the shape of the object with the animation with 3D stereoscopic technique when the object is close. However, with the adaptive IPD adjustment, they can see the 3D object regardless of how close the 3D object is. The large disparity can negatively affect naturalness of the visualization. The adaptive IPD adjustment method provided better visual comfort and naturalness than stereoscopic visualization with a fixed IPD. Due to these reasons, users preferred the adaptive IPD adjustment technique over 3D stereoscopic visualization with a fixed IPD and monographic visualization.

From the results of the third user study, the author concluded that the adaptive IPD adjustment method can provide effective 3D visualization with less visual fatigue for multiple users.

7.4 The Development of a Framework and its Prototype VR system.

The proposed software framework was designed to encapsulate the core components of the proposed interaction techniques, the display setup for multiple users, and the visual fatigue reduction technique. Based on the insights for multi-user interaction display setups, the framework can support various display setups for multiple users. Using the OST and AWMT, the PoV for VR rendering is adjusted based on the users’ movement. When the

PoV is located by the OST and AWMT, the framework can reduce visual fatigue using the adaptive IPD technique. Network communication and synchronization features are provided to support multiple devices. The fast file loader, the 2D and 3D graph generator, and the geometry loader were developed for visualization of virtual objects. The user studies in this thesis were implemented using the framework as well as a prototype VR system for multi-dimensional decision making. The VR system provided not only multi-user interaction, but also 2D and 3D graphs and geometric visualization, and a head-tracked interface.

7.5 Limitations of The Thesis

The studies in this thesis mainly discussed on how to improve 3D multi-user interactive visualization with a shared large-scale display including display setups, interactive visualization, and visual fatigue. Although this thesis makes a number of important contributions it also has a number of limitations, which are discussed in more detail in this section.

Firstly, the study for the display setups for multiple users was conducted with loosely coupled collaborative tasks (collaborative tasks for each user were slightly related, which users could complete independently). Tightly coupled collaborative tasks (collaborative tasks that are strongly related so users need to do them together) may not be suitable for a split screen.

Secondly, the Object Shift Technique (OST) requires a larger virtual environment than the conventional Mean Tracking (MT) method. The OST shifts virtual objects in the opposite direction of the PoV movements, so it requires a virtual environment at least twice as large compared to its absent condition.

Thirdly, the Activity-based Weighted Mean Tracking (AWMT) method performs similarly to the MT method in the worst cases as mentioned in the worst scenario in section 4.2.2.2. In addition, the methods support 3D movements but only 2D movements (including left-right and back-forth) were evaluated during the experiment. The author assumed vertical movement (up-down) in the VE may be the same as 2D movements. However, it might be possible that scene change in vertical movement is more abrupt due to a sudden jumping action, which could influence the user experience and performance.

Fourthly, the author assumed that the experiment with a single user for the third study is similar to a 3D multi-user visualization with a single PoV due to the similar system configuration. However, the results might be different between the two configurations. A pilot test was conducted for the Adaptive IPD adjustment technique and the participants answered that interactive visualization with adaptive IPD Adjustment was better than 3D stereoscopic visualization with fixed IPD. However, it might be possible that the results may differ with multiple users compared to the single user configuration tested in the experiment.

Fifthly, the framework requires manual process in setting up displays to build a VR system. The framework provides the display setup configurator to simplify building of the VR system. However, it still required manual work to set up the display because the framework cannot know how physical environment is set.

Sixthly, the author found that the framerate differs between the framework and devices, which might cause potential problems by missing packets. When the framerate of the framework is slower than devices, the framework can accumulate the command packets, and occasionally misses the command packets. The framework tries not to ignore the command packets as much as possible. However, packet loss can still occur, which may require users to perform input action again. Though this problem was partially solved by matching the framerate between the framework and the control devices, and other processes, it may not be solved perfectly because the framerate cannot be matched exactly.

Lastly, the prototype VR system was rigorously assessed with user study. The system was built to support the multi-dimensional objectives decision making. Due to the various types of data to visualize, the author had to mix 2D and 3D visual objects together in the same environment, which might cause visual fatigue. The author conducted a pilot study with a small number of users. The participants answered that they did not feel severe fatigue from the mixed virtual objects because the display screens are separated and big enough to focus on a single screen. However, it might require further investigation on if the mixture of 2D and 3D visualization would cause visual fatigue.

Chapter 8

Conclusion

This chapter concludes the dissertation. The author summarizes the presented work and describes directions for future research. The main goal of this Ph.D. was to improve 3D multi-user interactive visualization with a shared large-scale display. The main contributions of this thesis are listed below:

1. A literature review of multi-user interaction with a shared large-scale display and relevant areas. The review focused on display setups, interactive visualization, and 3D visual fatigue for multiple users. (Chapter 2)

2. Deeper insights into three display setups for multi-user interaction with a shared large-scale display. (Chapter 3)

3. Development of two novel multi-user interactive visualization techniques (the Object Shift Techniques and the Activity-based Weighted Mean Tracking method) that support interaction with multiple users and help to reduce the visual fatigue. (Chapter 4)

4. Development of an Adaptive Interpupillary Distance Adjustment technique that can reduce visual fatigue caused by the extreme disparity between the views of the users' left and right eyes. (Chapter 5)

5. Demonstration and user evaluation of three display setups (a shared view, a split screen, and a split screen with navigation information). The user study includes the evaluation of interaction performance, collaborative usability, and user preference. (Chapter 3)

6. Implementation and evaluation of the three novel interaction techniques (the Object Shift Techniques, the Activity-based Weighted Mean Tracking method, and the Adaptive Interpupillary Distance Adjustment technique). Each user study measured interaction performance, depth perception, visual fatigue, usability, and performance. (Chapter 4 and Chapter 5)
7. Development of a framework for supporting a multi-user interaction with a shared large-scale display and its application to multi-dimensional decision making VR system. The framework not only supports the novel interaction techniques mentioned above but also includes fundamental multi-user interaction functions such as head tracking, network synchronization, and 3D visualization. (Chapter 6)

The main results of each study and the development are summarized in section 8.1 and potential future works are introduced in section 8.2.

8.1 Summary of the thesis

In the first experiment (Chapter 3), the author observed the effects of display setups and the relationship between display setups and multi-user interaction. Most participants preferred having more information such as the partner's view and navigation information for collaboration. However, the preference did not relate to the interaction performance, overall usability, and workload since the shared view provides the best interaction performance and the overall usability and workload between display setups are similar. A shared view can still provide effective interaction performance in a collaboration task although it has a control conflict problem. Although the control conflict did not seem to have a significant impact on the collaboration because users tend to avoid the control conflict, it can cause mental demand and frustration. Therefore, an interactive visualization system will be preferred by users if it can provide sharable independent screens and navigation information for a shared large-scale display. However, a shared view can still support collaborative interaction with better performance and usability when individual controllers are given.

From the first study, the shared view was shown beneficial for multi-user interactive visualization when the exploration and discussion in a virtual environment require more information and space to display. In such a case, the PoV used for visualization should reflect different positions of multiple users. The Mean Tracking method that previous research employed cannot reflect individual users' movement in the VE because the PoV is calculated using the average of multiple users' locations. Therefore, the author proposed two interactive visualization techniques (Object Shift Technique and Activity-based Weighted Mean Tracking method) for multi-user interaction and evaluated them in the second user study. The second experiment evaluated the two interactive visualization techniques and the results showed that they can better support collaboration, improve interactivity, and provide acceptable visual comfort.

The third study was conducted to further reduce visual fatigue caused by 3D stereoscopic visualization of close virtual objects. Even when using the two interactive visualization techniques investigated in the second study, users still felt visual fatigue from the large disparity when they were close to the virtual objects. So, the author introduced a visual fatigue reduction technique for 3D stereoscopy. The author simulated visualization with a single PoV and tested it with a single user because of the similarity between a single user and a single PoV for multi-user interaction with a shared view. The user evaluation compared the new technique with monoscopic visualization and normal 3D stereoscopic visualization. The evaluation results showed that the adaptive IPD adjustment can reduce visual fatigue yet providing reasonable depth perception.

Along the course of conducting these studies, the author developed a software framework described in Chapter 6 and designed a set of experiments. The proposed framework architecture contains the three main ideas investigated through a series of studies. To show the utility of the framework, a demonstration application for multi-dimensional decision making was also developed using the framework.

Overall, in this thesis, to improve 3D multi-user interactive visualization with a shared large-scale display, deeper insights of display setups for multi-user interaction have been investigated. The two novel interactive visualization techniques and the visual fatigue reduction technique were developed. Finally, a software framework reflecting the proposed methods was developed together with a prototype VR application using the framework.

8.2 Future work

This thesis described how to improve 3D multi-user interactive visualization with a shared large-scale display in order to provide a better user experience to a group of users. In this section, the author presents future work that could be carried out to extend the thesis research.

In the future, the author plans to further examine the effect of the display setups on various virtual environments for multi-user interaction. In this thesis, the author selected a shared view for interactive visualization. However, the display setups might have a different impact on interactive visualization. When the user moves in the virtual environment, the split screen may be required to be relocated or to be fixed on the large screen. Or a shared view screen may provide better interaction for the environment.

In the second study, the author hypothesized that the more users participating in a collaborative task with the OST and the AWMT, the better performance and experience will be achieved, compared to the conventional MT method. While the reported experiment shows its benefit with three users, further experiments need to be carried out in the future to examine the superiority of these methods. Additionally, the different transition methods between active users need to be investigated in future study. While the linear interpolation was used for the weight variation, a polynomial, spline or cubic interpolation may be able to provide more seamless transition for multi-user interaction compared to the linear interpolation, which might reduce the inconsistency. Finally, the experiment was conducted for a short amount of time. The results on visual fatigue may differ under longer usage, which is also needed to be investigated in the future.

In terms of the visualization fatigue study, the author plans to improve the method to be applicable to more general stereoscopic visualization setup, and further investigate other factors that could be used as a metric for adaptively adjusting the IPD. Moreover, the author will look into integrating a gaze tracking system with the proposed method, which would provide a more immersive and realistic 3D stereoscopic viewing experience for the users.

Furthermore, the further evaluation of the prototype VR system will be carried out. Although the author conducted a pilot study with ordinary people to evaluate the prototype VR system in terms of visual fatigue and user interface on mobile devices, it is necessary to design the user study for experts for multi-dimensional decision making in order to improve the prototype VR system.

To conclude the author hopes this research can inspire those who aim to research 3D multi-user interactive visualization with a shared large-scale display and can lead to novel interactive visualization techniques for multiple users. The author also hopes this research can inspire future research directions that can enhance multi-user interaction to encourage people to interact and to enjoy virtual reality.

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Appendices

Appendix A

Questionnaire for Display Setups for Multiple Users in Chapter 3.

Pre-experiment questionnaires

Q1 How old are you?

Q2 Gender Selection

☐ Male
☐ Female
☐ Other

Q3 Have you experienced any mobile interface before?

☐ Smart-phone
☐ Tablet
☐ PDA
☐ Others ____________________
☐ I have no experience.

Q4 Have you experienced any virtual environment system?

☐ 3D stereoscopic visualization
☐ Large Display Virtual Environment
☐ Cave System
☐ Head Mounted Display(HMD)
☐ Others ____________________
☐ I have no experience.

Q5 Have you experienced any collaboration work using large-scale display?

☐ Yes
☐ No

Q6 Do you have any problem with moving?

☐ Yes
☐ No

Thank you!

Please complete the experiment before proceeding with the next questionnaire.

Post-Condition questionnaires

Q1 Choose case

- ☐ Case 1
- ☐ Case 2
- ☐ Case 3
- ☐ Case 4

Q2 Please answer based on your experience

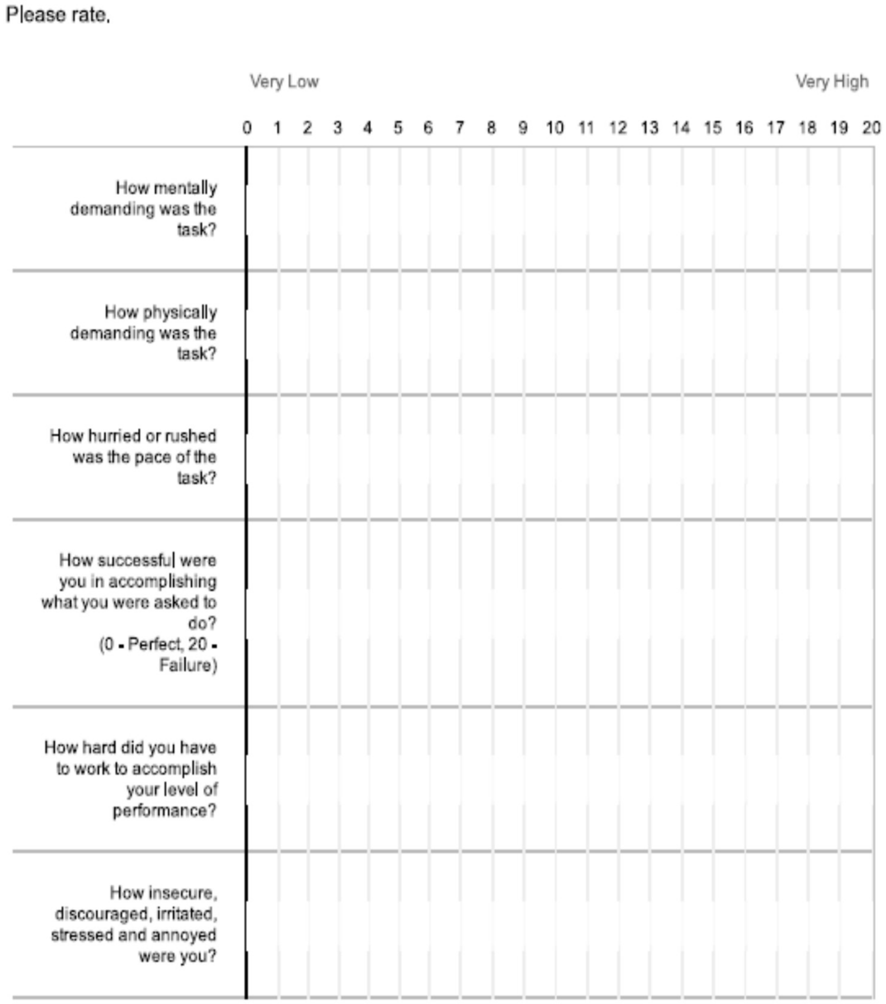
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I think that I would like to use this interaction frequently.	○	○	○	○	○
I found the system unnecessarily complex.	○	○	○	○	○
I thought the interaction was easy to use.	○	○	○	○	○
I think that I would need the support of another person to be able to use this interaction	○	○	○	○	○
I found the various functions in this interaction were well integrated.	○	○	○	○	○
I thought there was too much inconsistency in this interaction	○	○	○	○	○
I would imagine that most people would learn to use this interaction very quickly.	○	○	○	○	○
I found the technique very cumbersome to use.	○	○	○	○	○
I felt very confident using the interaction.	○	○	○	○	○
I needed to learn a lot of things before I could get going with this interaction.	○	○	○	○	○

Q3 Please answer based on your experience.

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
We were able to collaborate effectively	○	○	○	○	○	○	○
We were able to work independently to complete the task	○	○	○	○	○	○	○
It was easy to discuss the information we found	○	○	○	○	○	○	○
We were able to work together to complete the task	○	○	○	○	○	○	○
I was able to actively participate in completing the task	○	○	○	○	○	○	○
How well did the system support collaboration?	○	○	○	○	○	○	○
How well did the system support you to share particular information with your partner?	○	○	○	○	○	○	○
I was able to tell when my partner was looking at what I was browsing?	○	○	○	○	○	○	○

How well did the system support you to see/review what your partner was talking about?	○	○	○	○	○	○	○
The system was helpful in completing the given task	○	○	○	○	○	○	○
I was aware of what my partner was doing	○	○	○	○	○	○	○
My partner was aware of what I was doing	○	○	○	○	○	○	○

Q4 Please rate.



Please rate.

Very Low … Very High

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
How mentally demanding was the task?																					
How physically demanding was the task?																					
How hurried or rushed was the pace of the task?																					
How successful were you in accomplishing what you were asked to do? (0 - Perfect, 20 - Failure)																					
How hard did you have to work to accomplish your level of performance?																					
How insecure, discouraged, irritated, stressed and annoyed were you?																					

Q5 What do you like about this interaction when performing the given task? Why?

Q6 What do you dislike about this interaction when performing the given task? Why?

Post Questionnaires

Q1 Please complete the experiment before proceeding with the next questionnaire.

Q2 Select on the factor that represents the more important contributor to workload for the task

- ○ Mental Demand
- ○ Physical Demand

Q3 Select on the factor that represents the more important contributor to workload for the task

- ○ Mental Demand
- ○ Temporal Demand

Q4 Select on the factor that represents the more important contributor to workload for the task

- ○ Mental Demand
- ○ Performance

Q5 Select on the factor that represents the more important contributor to workload for the task

- ○ Mental Demand
- ○ Effort

Q6 Select on the factor that represents the more important contributor to workload for the task

- ○ Mental Demand

- Frustration

Q7 Select on the factor that represents the more important contributor to workload for the task

- Physical Demand
- Temporal Demand

Q8 Select on the factor that represents the more important contributor to workload for the task

- Physical Demand
- Performance

Q9 Select on the factor that represents the more important contributor to workload for the task

- Physical Demand
- Effort

Q10 Select on the factor that represents the more important contributor to workload for the task

- Physical Demand
- Frustration

Q11 Select on the factor that represents the more important contributor to workload for the task

- Performance
- Effort

Q12 Select on the factor that represents the more important contributor to workload for the task

- ○ Performance
- ○ Frustration

Q13 Select on the factor that represents the more important contributor to workload for the task

- ○ Performance
- ○ Temporal Demand

Q14 Select on the factor that represents the more important contributor to workload for the task

- ○ Temporal Demand
- ○ Effort

Q15 Select on the factor that represents the more important contributor to workload for the task

- ○ Temporal Demand
- ○ Frustration

Q16 Select on the factor that represents the more important contributor to workload for the task

- ○ Effort
- ○ Frustration

Q17 Which interaction method did you prefer? Please rank the condition (1: best - 4: worst)

______ Case 1
______ Case 2
______ Case 3
______ Case 4

Q18 Why do you think that the condition is the best technique for you? (Performance, individual view, Overall View, less visual fatigue, less visual distortion)

Q19 Did you have any problem during the experiment?

Q20 Any other comments on the experiment?

Appendix B

Questionnaire for Interactive Visualization for multiple users presented in Chapter 4.

Pre-experiment questionnaires

How old are you?

Gender Selection

○ Male
○ Female
○ Other

Have you experienced any mobile interface before?

☐ Smart-phone
☐ Tablet
☐ PDA
☐ Others ____________________
☐ I have no experience.

Have you experienced any virtual environment system?

☐ 3D stereoscopic visualization
☐ Large Display Virtual Environment
☐ Cave System
☐ Head Mounted Display(HMD)
☐ Others ____________________
☐ I have no experience.

Do you have any problem with moving?

- ○ Yes
- ○ No

Thank you!

Please complete the experiment before proceeding with the next questionnaire.

Post-condition questionnaires

Choose case

- ○ Case 1- Median Technique
- ○ Case 2- Object Shift
- ○ Case 3- Median Technique + Weight-Based
- ○ Case 4- Object Shift + Weight-Based

Please answer based on your experience

	Strongly Disagree		Neutral		Strongly Agree
I think that I would like to use this interaction frequently.	○	○	○	○	○
I found the system unnecessarily complex.	○	○	○	○	○
I thought the interaction was easy to use.	○	○	○	○	○
I think that I would need the support of another person to be able to use this interaction	○	○	○	○	○
I found the various functions in this interaction were well integrated.	○	○	○	○	○
I thought there was too much inconsistency in this interaction	○	○	○	○	○
I would imagine that most people would learn to use this interaction very quickly.	○	○	○	○	○
I found the technique very cumbersome to use.	○	○	○	○	○
I felt very confident using the interaction.	○	○	○	○	○
I needed to learn a lot of things before I could get going with this interaction.	○	○	○	○	○

Please answer based on your experience

	Strongly Disagree					Strongly Agree
I felt depth perception	○	○	○	○	○	○	○

Please answer based on your 3D stereoscopic experience

	No			Sometimes			Frequently
I got stressed	○	○	○	○	○	○	○
I felt my eyes are tired	○	○	○	○	○	○	○
I had uncomfortable vision	○	○	○	○	○	○	○
I had a headache	○	○	○	○	○	○	○
I had eye irritation	○	○	○	○	○	○	○
I had burning eyes	○	○	○	○	○	○	○
I had neck pain	○	○	○	○	○	○	○
I had pulling feeling of the eyes	○	○	○	○	○	○	○
I had ache in or behind the eyes	○	○	○	○	○	○	○
I had watery eyes	○	○	○	○	○	○	○

Please answer based on your experience

	Strongly Disagree						Strongly Agree
Were you trying to help another user to finish his work?	○	○	○	○	○	○	○

What do you like about this interaction when performing the given task? Why?

What do you dislike about this interaction when performing the given task? Why?

Post-Experiment Questionnaires

Which interaction method did you prefer? Please rank the condition (1:best - 4: worst)

______ The first interaction technique
______ The second interaction technique
______ The third interaction technique
______ The fourth interaction technique

Why do you think that the condition is the best technique for you? (Performance, less visual fatigue, less visual distortion and so on)

Were the task sequences same in each condition?

- ○ Yes
- ○ No

Please answer based on your experience

	Very different			I don't know			Same
Does the display of the 3D cube look different in each condition?	○	○	○	○	○	○	○

If different, how is the display of the 3D cube in each condition different?

Did you have any problem during the experiment?

Any other comments on the experiment?

Appendix C

Questionnaire for Reducing 3D visualization Fatigue in Chapter 5.

Pre-experiment questionnaires

1. Age:

2. Gender: Male / Female / Other

3. Please check ALL of the 3D (Three-dimensional) stereoscopic visualization experience you had before:

☐ 3D stereo movie at the cinema

☐ 3D TV

☐ Immersive 3D stereoscopic display (e.g. CAVE, Visionspace, HMD)

☐ Interactive 3D stereoscopic game or entertainment

☐ Others ______________________

☐ Have no previous experience with 3D stereoscopic visualization, at all.

4. Do you have any eyestrain now?

☐ YES

☐ NO

---

5. Can you perceive 3D depth while watching 3D stereoscopy?

☐ Yes

☐ No

Post-condition questionnaires

First condition questionnaire

	Strongly Disagree		Neutral		Strongly Agree
I felt like the airplane was moving towards me popping out of the screen.	1	2	3	4	5
While watching the scene...					
I perceived the 3D depth of the scene.	1	2	3	4	5
I thought that the scene looked natural.	1	2	3	4	5
I felt eyestrain.	1	2	3	4	5

Second condition questionnaire

	Strongly Disagree		Neutral		Strongly Agree
I felt like the airplane was moving towards me popping out of the screen.	1	2	3	4	5
While watching the scene...					
I perceived the 3D depth of the scene.	1	2	3	4	5
I thought that the scene looked natural.	1	2	3	4	5

I felt eyestrain.	1	2	3	4	5

Third condition questionnaire

	Strongly Disagree		Neutral		Strongly Agree
I felt like the airplane was moving towards me popping out of the screen.	1	2	3	4	5
While watching the scene...					
I perceived the 3D depth of the scene.	1	2	3	4	5
I thought that the scene looked natural.	1	2	3	4	5
I felt eyestrain.	1	2	3	4	5

Post-experiment questionnaires

1. Which condition did you prefer? Please write down the conditions (#1, #2, #3) in the order of the most preferred to the least preferred.

Most preferred	Second place	Least preferred

2. Please write down the conditions (#1, #2, #3) in the order of how much you perceived 3D depth, from most to least.

Most	Second place	Least

3. Did you have any problem during the experiment?

4. Any other comments on the experiment?