# Designing and evaluating ubiquitous wearable virtual reality

by

Aryabrata Basu

(Under the Direction of Kyle Johnsen)

## Abstract

Navigating spaces is an embodied experience. Examples can vary from rescue workers trying to save people from natural disasters; a tourist finding their way to the nearest coffee shop, or a gamer solving a maze. Virtual reality allows these experiences to be simulated in a controlled virtual environment. However, virtual reality users remain anchored in the real world and the conventions by which the virtual environment is deployed influence user performance. There is currently a need to evaluate the degree of influence imposed by extrinsic factors and virtual reality hardware on its users. We conducted a series of four user studies exploring ergonomic, environmental, human, and technical factors and their effects on immersive virtual reality user performance and general usability.

Traditionally, virtual reality experiences have been deployed using Head-Mounted Displays with powerful computers rendering the graphical content of the virtual environment; however, user input has been facilitated using an array of human interface devices including Keyboards, Mice, Trackballs, Touchscreens, Joysticks, Gamepads, Motion detecting cameras and Webcams. Some of these HIDs have also been introduced for non-immersive video games and general computing. Due to this fact, a subset of virtual reality users has greater familiarity than others in using these HIDs. Virtual reality experiences that utilize gamepads (controllers) to navigate virtual environments may introduce a bias towards usability among virtual reality users previously exposed to video-gaming.

This dissertation presents a design for a ubiquitous virtual reality framework and evaluates related user studies conducted using our framework with general audiences. Among our findings, we reveal a usability bias among virtual reality users who are predominantly video gamers. Beyond this, we found a statistical difference in user behavior between untethered immersive virtual reality experiences compared to untethered non-immersive virtual reality experiences.

INDEX WORDS: Virtual Reality, Computer science

# DESIGNING AND EVALUATING UBIQUITOUS WEARABLE VIRTUAL REALITY

by

ARYABRATA BASU

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ARYABRATA BASU

Approved:

Co-Major Professor: Kyle Johnsen
Co-Major Professor: Walter Potter

Committee: Khaled Rasheed
Tianming Liu

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
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# Designing and evaluating ubiquitous wearable virtual reality

Aryabrata Basu

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*For my beloved wife Dipannita and my newborn son Aaron*

&

*For my infinitely patient Meowsy*

# Acknowledgments

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This dissertation is a result of the culmination of over 7 years of research looking into various virtual reality systems and immersive applications, their deployment mechanisms, and overall usability. This work draws inspiration upon the previous works of Dr. Randolph (Randy) Pausch, whose seminal work on the democratization of VR hardware and software in 1991 became our guiding principle. I would like to pay my homage to Randy. May his soul rest in peace.

I am also very thankful to Dr. Ivan Sutherland, who has graciously permitted me to reuse images of his head-mounted 3D display (HMD), the very first of its kind. In 1968, Dr. Sutherland built the first HMD system that generated binocular imagery rendered appropriately for the position and orientation of the moving head. We still use the very same principle to drive modern HMDs. As a matter of fact, the year 2018 is the 50th anniversary of the original head-mounted display technology.

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Lastly, to life. I have been shaped profoundly by the struggles in my life to know the unknown. I hope I have uncovered at least a bit of it. For all I realize now is that everything is connected as described by Albert Einstein. *Natura Naturans!*

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

*"Rather than love, than money, than fame, give me truth."*

— Henry David Thoreau

Virtual Reality (VR) is the art of substituting real-world sensory information with artificial stimuli such as 3D visual imagery, spatialized sound, and force or tactile feedback and packaging it all together inside a virtual environment (VE). In 1968, Ivan Sutherland implemented the first VR system that allowed users to occupy the same space as virtual objects using wireframe graphics and an Head-mounted display (HMD) [Sutherland, 1968]. Since then, the VR community has advanced the quality of computer-generated graphics, built sensors to update the user's viewpoint (head gaze) inside the VE, and implemented high-end spatial audio playback capability. However, more recently VR systems have become more prevalent due to the adaptation of mobile communication platforms (smartphones) as immersive displays and video-gaming devices, such as gamepads, as controllers. These new generations of VR systems have enabled us to deploy highly immersive and portable virtual experiences outside of controlled laboratory settings.

There have been very few research studies that have looked into usability and acceptance of such ubiquitous VR systems by general audiences. Furthermore, the current design trends of ubiquitous VR systems do not address the core issues of VR usability, such as simulator sickness and user encumbrances, leading us to the conjecture that the majority of users may not yet accept VR systems.

## 1.1 The problem

We take the term *immersive* in VR to refer to a VE which appears to surround the user's peripheral vision. Applications of immersive VR have developed significantly over the span of the last decade [see Chapter 2]. From immersive molecular modeling [Drees et al., 1996] to manifold composition visualization [Kaper and Tipei, 1998] to evaluating travel techniques [Bowman et al., 1998a] to building trust in human interactions [George et al., 2018] to performing laparoscopic surgery [Huber et al., 2018], many research projects and applications have leveraged immersive VEs as the basis of their studies. The core of preparing any immersive VR experience falls back to drawing a VE with the perspective of the user at a fast update rate and a high resolution. The user is then able to manipulate the content of the VE by interacting with it in VR. Currently, to have an effective VR experience, the user needs to wear multiple hardware interfaces/devices. A traditional immersive VR system deployed in a laboratory setting would include the following setup: (1) a HMD or a rear wall projected display like CAVE [Cruz-Neira et al., 1992] that displays the VE (2) a tracking system that tracks the user's physical movement mapped onto the VE. Historically, a VR setup of this sort suffers from issues of high infrastructure maintenance, poor deploy-ability, and scalability [Bowers et al., 1996; Hindmarsh et al., 2000]. User encumbrance issues, such as being tethered to a limited tracking area, results in a lesser range of movement for the user using the VR system. From a user experience standpoint, a higher number of hardware interfaces introduces fatigue due to increase in overall weight of the system and induces cyber-sickness [LaViola Jr, 2000] resulting in decreased usability thus leaving the users with less motivation to continue having the immersive experience.

Position tracking of users in VR is limited to availability of physical space by design and it requires higher demands on infrastructure. One way to solve these issues is to facilitate user input using an array of available human interface devices (HID) including keyboards, mice, trackballs, touchscreens, joysticks, gamepads, motion detecting cameras, and webcams. Some of these HIDs have also been introduced for non-immersive video games and general computing. Due to this fact, a subset of VR users has greater familiarity than others in using these HIDs. VR experiences that utilize gamepads (controllers) to navigate VEs possibly introduce a bias towards usability among VR users previously exposed to video-gaming.

Because of the increasing prevalence of ubiquitous VR systems, we need to design and evaluate comprehensive, immersive ubiquitous VR experiences that acknowledge the existing usability bias amongst immersive VR users. Furthermore, we need to understand better how extrinsic factors play a role in affecting user performance in an immersive VR experience using such ubiquitous VR systems.

## 1.2 Potential solutions for a more usable VR

The VR community currently has evolved to a point where the next order of problem-solving is related to 3D user-interfaces (3DUI) and human-centric usability issues. The chronology of VR community activity [DBLP, 1993] suggests that the community started looking more closely into usability aspects of VR systems with an emphasis on effective interfaces. The goal became to investigate and design guidelines and evaluate metrics for 3DUIs that maximize user performance while keeping the cybersickness issues at bay. Sutcliff et al. suggested assessing the usability of VR user interfaces [Sutcliffe and Deol, 2000] based on a theory that extends Norman's model of action [Norman, 1986] by interacting with virtual spaces. This trend moved more into investigating usability on desktop VR environments [Sebok et al., 2004]. As VR hardware evolved with time becoming smaller in deployment footprint, a new trend in usability studies started looking into wearable devices and their contribution to better immersive VR usability [Kossyk et al., 2011]. While there have been usability studies focusing on specific user-interfaces and measuring their effectiveness, a generalized study design comparing immersive and non-immersive VR perspective has not been implemented yet. The idea behind this fundamental comparison between immersive versus non-immersive user perspective showcases the value-add in HMD based (immersive) versus desktop based (non-immersive) VR environments. This dissertation works towards clarifying the value-add in having HMD based immersive VR experiences. The affordability and usability presented by VR design trends that incorporate smart devices and gamepads (controllers) represent a giant leap in democratizing VR. We believe, by better understanding user behavior and extrinsic factors affecting VR users, we are stepping in the right direction toward implementing true unencumbered, ubiquitous VR experiences.

## 1.3 Dissertation statement

*New generations of VR systems have enabled us to deploy highly immersive and portable virtual experiences outside of controlled laboratory settings. However, there have been very few research studies that have looked into usability and acceptance of such ubiquitous VR systems by the general audience. Furthermore, the design of ubiquitous VR systems does not address the core issues of VR usability such as simulator sickness and user encumbrances leading us to the conjecture that VR systems may not yet be accepted by the majority.*

*This dissertation discusses our work involved in the design and evaluation of both custom designed and commercially available ubiquitous VR systems, and revealed issues that may better inform future research and design.*

## 1.4 Overview of our solution

This dissertation presents my contributions as follows:

- The Ubiquitous Collaborative Activity Virtual Environment (UCAVE), a framework conceptualized with universally accessible technology to enable untethered and portable VR experiences [see chapter 3].
- Designing and evaluating VR user studies in order to further evaluate ergonomic, environmental, human, and technical factors affecting users in immersive VR ex-

periences.

- Understanding the core impact of deploying immersive VR experiences via HMD technology on user trajectory patterns (behaviors) in solving a spatial navigation problem inside VR.

Our work focused on implementing low encumbrance ubiquitous VR systems for everyone. We began to conceptualize mobile VR systems that are portable and could readily put someone into immersive VR. In our pursuit of a mobile VR design, we incorporated a light-weight HMD device connected (wired) to a smartphone to build a wearable display that one can wear quite comfortably. Once immersed, the user interacts with the content by rotating their head naturally to look around inside the VE. Such form of head-rotation based interaction is made possible by the software on the smartphone that renders each frame of the VE synced to the sensor responsible for detecting pan and tilt motion of the smartphone. We added real-time hand tracking to provide direct means of interaction inside VEs. We call this paradigm of portable VR setup "the UCAVE". The idea of personalized VEs that are shared with many users became the baseline of our design philosophy.

Next, we conducted a series of formative user studies to evaluate our UCAVE platform and gained valuable user feedback. Our first study (Study I - a study of ergonomic factor) explored the ergonomics of an immersive VR setup by studying whether the presence of a perceived tether affected user performance in immersive VR. Our findings from this study established the need for an untethered immersive VR apparatus. Once we achieved a level of sophistication in our system design, we then focused our attention on studying environmental factors by creating VEs to match indoor/outdoor real-world settings relatively. Our findings from this study showed significant difference in user performance whether the VE matched real-world environment or not. Furthermore, we noticed that a matched outdoor setting (outdoor as physical space and outdoor as the VE) seems to be the best performing setting for participants. We were encouraged by our previous results and turned our attention to human factors affecting user performance in immersive VR. We considered self-reported physical fitness as our metric for evaluating user performance. Our findings from this study showed no correlation between perceived physical competence and user performance in immersive VR. However, this study established the need to look into the gaming profile of VR users as a predictor of success in immersive VR experiences. Taking our findings from studies exploring ergonomic, environmental, and human factors, we proposed our final user study designed to examine the influence of technical factors affecting user performance in immersive VR. We aimed explicitly at exploring immersive versus non-immersive 3DUIs affecting user performance. Our findings from our final study revealed usability bias amongst participants who are also video-gamers because of their familiarity with the gamepad interface. This subset of participants solved the maze more quickly than non-gamer participants. We also found a significant statistical difference in user behavior between immersive and non-immersive VR experiences.

These findings taken together provide meaningful contributions to both users and designers in the VR community.

## 1.5 Overview of dissertation

The rest of the dissertation is organized as follows:

- Chapter 2 explores the history and evolution of virtual reality systems in general and examines a subset of ubiquitous VR systems research as a new subfield of VR research stemming from the advent of smartphone revolution circa 2011. The later sections of this chapter will discuss key components of VR experience, common VR terminology, and current trends in ubiquitous VR.
- Chapter 3 dives into conceptualization of ubiquitous VR as a framework and presents a custom designed ubiquitous VR system prototype and its brief evolution [Basu et al., 2012b].
- Chapter 4 introduces Study I, a study of ergonomic factor, using UCAVE as our platform. This study explores the ergonomics of immersive VR setup and investigates whether the presence of a perceived tether affects user performance in immersive VR. The study design is presented, and the results are analyzed.
- Chapter 5 introduces Study II, a study of environmental factor, using UCAVE as our platform. This study explores the impact of environmental factors on user performance by creating VEs to match indoor/outdoor real-world setting relatively. The study design is presented, and the results are analyzed.
- Chapter 6 introduces Study III, a study of human factor, using a commercially available ubiquitous VR system. This study explores the impact of human factors

such as self-reported physical fitness assessment, affecting user performance in immersive VR. The study design is presented, and the results are analyzed.

- Chapter 7 introduces Study IV, a study of technical factor, using a commercially available ubiquitous VR system. This study examines immersive and non-immersive user interfaces affecting user performance in immersive VR. The study design is presented, and the results are analyzed. Furthermore, we conduct extended analysis on recorded user trajectory data. To that end, we define mathematical trajectory features, such as distance traveled, decision points reached inside the VE, positional curvature, head rotation amount, and coverage of the VE extracted from user trajectory and head gaze information.
- Chapter 8 reflects on the implications of our current work and lays a foundation for future work.

# Chapter 2

# Review of the Literature

> *"Equipped with his five senses, man explores the universe around him and calls the adventure Science."*
>
> — Edwin Powell Hubble, The Nature of Science, 1954

## 2.1 Background

In this section of this chapter we are going to review a brief history of VR systems and applications and discuss how they evolved over time. After that, we will familiarize ourselves with key components of VR experiences and common VR terminology. Finally, we discuss the evolution of ubiquitous VR as a subfield of VR and its current trends.

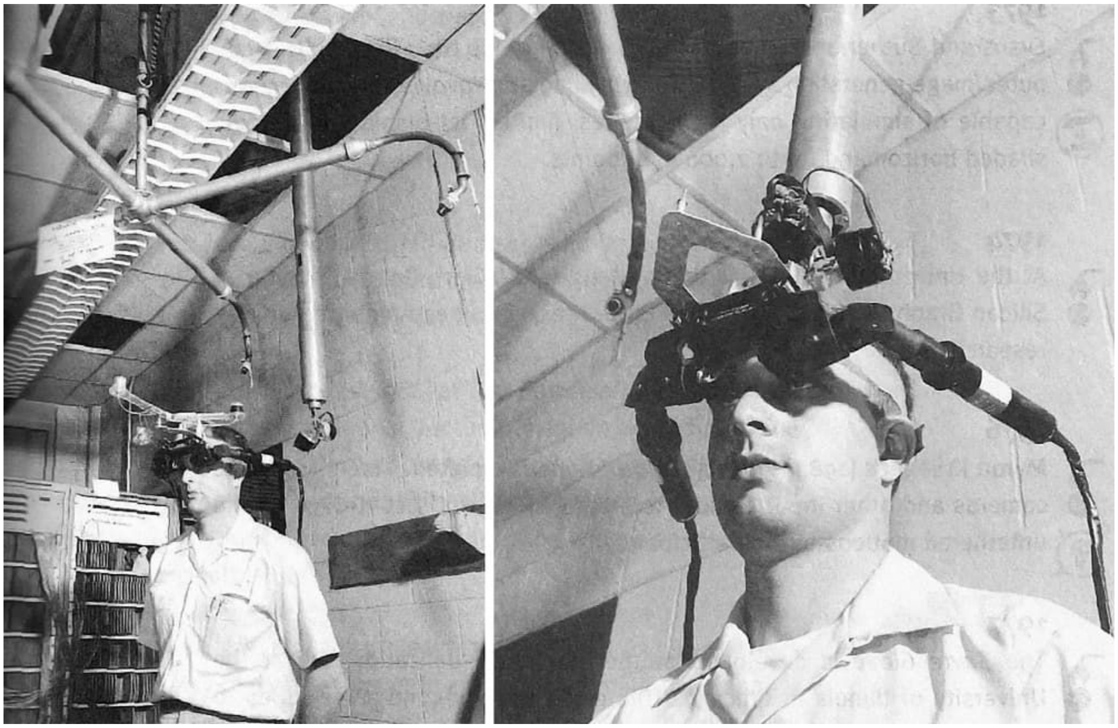


Figure 2.1: Ivan Sutherland's head-mounted 3D display (c. 1968). The display had a suspending counterbalance mechanical arm and used ultrasonic transducers to track the head movement. (Left) The system in use. (Right) The various parts of the three-dimensional display system. Images reproduced from Sutherland (1968), with permission from Dr. Ivan Sutherland.

### 2.1.1 A brief history of VR

Computer graphics are an essential aspect of modern computation platforms. At the turn of the last century, it was required that engineers, architects and designers have the common know-how to operate a graphics workstation in their respective workplaces. With the rapid progress of microprocessor technology, it became possible to produce three-dimensional computer graphics that can be manipulated in quasi real-time. This technology, which enabled interactions with three-dimensional virtual objects, immediately made its way into several different mainstream industry including design, visualization and gaming. This chapter chronicles the crucial moments in the field of VR and its evolution. We will go through the timeline of major VR technological shifts and events to understand and appreciate the progress of the field of VR.

In 1963, Ivan Sutherland introduced Sketchpad [Sutherland, 1963], a computer program that used an x-y vector display and tracked light pen for computer-aided drawing. This was arguably the first interactive graphical user interface connected to a computer. Two years later, Sutherland described the 'ultimate display' as the "a room within which the computer can control the existence of matter" [Sutherland, 1968]. He added, "a chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal." Eventually, Sutherland and his student Bob Sproull created the first HMD system for interactive computer graphics. This system generated binocular imagery that was rendered appropriately for the position and orientation of the moving head. As shown in Figure [2.1], the display was suspended from a counterbalanced robotic arm and ultrasonic transducers were used to track the natural movement of the head. This was the first time in the history of computer graphics that people could see into a computer generated virtual world. Sutherland said "make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer's actions" [Sutherland, 1968]. This laid the foundation for modern VR applications specifically for immersive VR. Modern VR systems have widespread application domains ranging from simulation and training, industrial design, exposure therapy, surgical planning and assistance, education, and video games. To understand the current trends in the field of VR, it is important to study the history of technologies from which the field of VR has evolved. By exploring the important milestones that have led to the advent of VR technology, the source of many current endeavors becomes evident. We shall see that all the basic elements of VR had existed since 1980, but it took high-performance computers, with their powerful image rendering capabilities, to make it work. This trend continued into the late 2000s until the emergence of smartphones. By 2011 the possibility of having completely untethered immersive VR experience was rising. The section that follows represents a timeline (from 1916-2015) in the development of VR as a field.

The timeline of VR technology and applications showcases important milestones in the field of VR. It includes personal achievements of scholars in the field as well as industrial accomplishments. But there is more to this timeline, for example the gap (approximately 17 years) between Sutherland creating the first HMD in 1965 and the first actual application of an HMD in the form of VCASS in 1982 shows us that computer graphics technology was not ready in 1965. Another interesting trend occurs around in the late 2000s when the mass market was ripe with touch-based smartphone technology. There emerges the need to use the smartphone technology as an inexpensive VR display. The advantage lies in the fact that the smartphones have inbuilt sensors like gyroscope, inertial measurement unit (IMU), and magnetometer to enable sensor fusion, which offers seamless head rotation tracking. Through advances in technology and democratization on an industrial scale, modern day VR systems have become portable and more ubiquitous. The concept of portable, light-weight, easily accessible VR systems is not a very

Table 2.1: VR timeline

| | |
|---|---|
| 1916 | U.S. Patent 1183492 is awarded for a head-based periscope display (WEAPON) to Albert B. Pratt |
| 1929 | Advent of the first mechanical flight simulator by Edward Link. Instead of flying short winged aircrafts also known as Penguin trainers, pilots were made to sit in a replica cockpit with every instrument panel replicated. This is an example of an early adoption of VR technology. |
| 1946 | The first digital computer ENIAC was developed at the University of Pennsylvania. |
| 1956 | Morton Heilig created a multi-sensory simulator using pre-recorded film in color and stereo. He augmented binaural sound, scent, wind and vibratory experiences. It was a complete experience, except that it was not an interactive system. |
| 1960 | U.S Patent 2955156 was awarded to Morton Heilig for a stereoscopic television apparatus which closely resembled the concept of HMDs. |
| 1961 | Philco engineers Comeau and Bryan create an HMD which follows head movement to follow a remote video camera viewing system. This is an early example of telepresence system. |
| 1963 | Ivan Sutherland creates the Sketchpad. This is the world's first interactive computer graphics application which can select and draw using the light pen in addition to keyboard input. |
| 1964 | General motors corp. begins research on the Design Augmented by Computer (DAC) system, an interactive application for automotive design. |
| 1965 | Ivan Sutherland explains the concept of his ultimate display in which the user can interact with objects in a hypothetical world which does not conform with our physical reality. |
| 1967 | The first prototype of a force-feedback system realized at the University of North Carolina (UNC). Inspired by Sutherland's ultimate display concept. Fred Brooks initiated GROPE to explore the use of kinesthetic interaction as a tool for helping biochemist feel interactions between protein molecules. |
| 1968 | Ivan Sutherland publishes "A Head-mounted Three-Dimensional Display" describing his development of tracked stereoscopic HMD. The display uses mini cathode ray tubes with optics to present separate image for each eye with mechanical and ultrasonic tracking. |

Table 1.1: VR timeline (cont.)

| | |
|---|---|
| 1972 | Pong, developed by Atari, brings real-time multiplayer interactive graphics to the public. |
| 1973 | Novoview, the first digital computer image-generation system for flight simulation was delivered by the Evan and Sutherland Computer Corp. It was only capable of simulating night scenes with limited display to a single shaded horizon. |
| 1974 | Jim Clark, who is a future founder of Silicon Graphics, Inc. submits his thesis on HMD research and development under the supervision of Dr. Ivan Sutherland. |
| 1976 | Myron Krueger created artificial reality called Videoplace. This system captured the silhouettes of the users from the cameras and projected them on a large screen. The users were able to interact with each other's silhouettes as their positions were mapped to the 2D screen's space. This would be arguably the first example of collocated collaborative VR, in which locally tracked users were able to interact inside the virtual world. |
| 1977 | The Sayre Glove was developed at the Electronic Visualization Lab at the University of Illinois at Chicago. This glove uses light-conductive tubes to transmit varying amounts of light proportional to the amount of finger bending thus estimating the user's hand configuration. The same year Commodore, Apple, and Radio Shack announced their line of personal computers for general purpose computing at home. |
| 1979 | Eric Howlett develops the LEEP (Large Expanse Enhanced Perspective) system for implementing the optics to deliver a wide field of view from a small display. This technology will be later integrated into early HMDs developed at NASA (VIVID display). |
| 1981 | Silicon Graphics, Inc. is founded by Jim Clark and his students at Stanford to produce high-speed, cost effective, graphics workstations to be used at VR facilities. Super Cockpit becomes operational at Wright Patterson Air Force Base. The Super Cockpit includes a see-through, head display mounted to the pilot's helmet. As pilots look in different directions, their vision is augmented with relevant information. In the same year, at MIT, the stereoscopic workspace project team begins work on an early augmented reality display that allows users to explore subject matter such as 3D drawing, architectural blueprint and 3D layout of computer chips. The device leveraged a half-silvered mirror to superimpose a computer image over the real-world objects such as the user's hands. |

Table 1.1: VR timeline (cont.)

1982

Sara Bly in her doctoral thesis proposes to use sound to represent large data sets. She classifies non-ordered multivariate data sets from which she creates discrete auditory events. She effectively mapped a number of parameters within the dataset to specific parameters of sound. This early sonification of laid the ground work for sound generation and representation in VR. In the same year, Thomas Furness at the US Air Force's Armstrong Medical Research Laboratories developed the Visually Coupled Airborne Systems Simulator (VCASS) – an advanced flight simulator. The pilots wore a HMD that augmented the out-of-sight window view by graphically describing target or flight path information.

1983

Mark Callahan at MIT develops one of the early HMD style VR systems outside of Sutherland's work.

1984

Scott Fisher is hired by NASA Aerospace Human Factors Research Division to create the Virtual Interface Environment Workstation (VIEW) lab. In the same year, VPL Research, Inc. is founded by Jaron Lanier, who also happens to be the person to coin the term virtual reality. NASA's VIEW lab contracts VPL Research to work on DataGlove and EyePhone. EyePhones are HMDs that leveraged LEEP optics. At the same time, VIVID display was created at NASA Ames with off-the-shelf technology: a stereoscopic monochrome HMD.

1987

Jim Humphries, lead engineer for the NASA VIEW lab, designed and prototyped the original BOOM, which is later commercialized by Fake Space labs in 1990. At the same time, Polhemus, Inc. introduces the Isotrak magnetic tracking system. This tracking system detects and reports the location and orientation of a small, user worn sensor.

1989

VPL announces RB-2, a complete virtual reality system. Autodesk, Inc. announces their CyberSpace project, a 3D world creation program for PC. In the same year, Mattel introduces PowerGlove for the Nintendo home video game system. This device becomes more popular among DIY VR enthusiasts.

1990

A system commercialized by Fake Space Labs, the BOOM is a small box containing two cathode-ray tube (CRT) monitors that can be viewed through the eyepieces. The user holds the box close to the eyes and a mechanical arm attached to the box tracks the position and orientation of the box. In the same year, NASA Ames Research Labs developed a VR application, the Virtual Wind tunnel, to observe and investigate flow-fields of fluids for better aerodynamic design, with the help of DataGlove and BOOM.

Table 1.1: VR timeline (cont.)

| | |
|---|---|
| 1991 | Virtual Research System, Inc. releases the VR-2 flight helmet. This was the first time when HMD price point came down to less than ten thousand USD. |
| 1992 | Projection VR is presented at SIGGRAPH'92 as an alternative to head-based displays. The main attraction was the CAVE system. CAVE is a virtual reality and scientific visualization system using multiple wall projected stereoscopic images as opposed to HMDs. It introduced the superior quality and resolution of viewed images and has much higher field of view in comparison to HMD based systems. |
| 1993 | The first two academically oriented conference are held for the VR community. The VRAIS'93 in Seattle and Research Frontiers in Virtual Reality IEEE workshop in San Jose. Later VRAIS and Research Frontiers in VR simply merged to be known as IEEE VR. Also, SensAble devices releases the first PHANTOM device. The PHANTOM is a low-cost force display device developed at MIT. |
| 1994 | The VROOM venue at SIGGRAPH demonstrates more than 40 applications running in CAVE VR system. |
| 1995 | Virtual I/O breaks the one thousand dollar price barrier for a HMD with VIO displays. These displays include an inertial measurement unit providing the head rotation information. |
| 1996 | Ascension Technologies corp. introduces the MotionStar wireless magnetic tracking system at SIGGRAPH'96. This new system had receivers for 14 different parts of the body and was targeted for largely motion capture industry. |
| 1998 | Disney opens up its DisneyQuest family arcade centers. These centers featured both HMD based and projection-based VR systems. In the same year, the first six-sided CAVE-style display is installed at the Swedish Royal Institute of Technology, Center for Parallel Computers. |
| 1999 | The ARToolKit, a free open source tracking library, primarily targeted for Augmented Reality applications, is released with collaboration between the HIT lab and the ATR Media Integration. Although designed for AR, the tracking library provides inexpensive solution to do position tracking with just a webcam. |
| 2000 | The first six-sided CAVE system in North America was installed at Iowa State University. |

Table 1.1: VR timeline (cont.)

| | |
|---|---|
| 2007 | Google introduced Street View, its web based 360 degrees panoramic views of street level images. These images are highly effective in simulating the immersive experience when rendered through its 3D stereoscopic mode later announced in 2010. |
| 2011 | Our work started here*. |
| 2012 | Fov2Go project is introduced at University of Southern California, MxR lab. It is software and hardware kit that supports the creation of immersive virtual reality experiences using smartphones. The same year, Palmer Luckey launched a VR kickstarter campaign to crowdfund the Oculus Rift DK1 HMD. This was the first time that a HMD design was offered commercially for a price point of three hundred USD. |
| 2013 | Valve discovered and freely shared the breakthrough of low-persistence displays which make lag-free and smear-free display of VR content possible. |
| 2014 | Facebook purchases Oculus VR for two billion USD. |
| 2015 | HTC and Valve corp. together announce the VR system HTC Vive and controllers. The system includes tracking technology called Lighthouse, which utilizes wall-mounted base stations for positional tracking using infrared light. |

new concept. In 1991, Randolph Pausch proposed his '5 dollar a day' VR system [Pausch, 1991a] for everyday use. He built this system using the then available video-gaming apparatus. The Pausch approach sparked a democratizing movement in VR technology.

In 2011, before we see a trend of leveraging smartphone technology as primary VR display by commercial entities, the VR research community paved the way. Basu et.al built a system that allowed untethered portability and instant deployment of immersive VR experiences [Basu et al., 2012a]. This system used a smartphone device as the display and its internal IMU sensors tracking head orientation. For the first time, a truly untethered VR deployment was achieved outside of a controlled laboratory setting. This setup provoked a host of other researchers to follow suit. For example, Evan Suma's MuVR [Thomas et al., 2014b] system has a similar build that support low-cost, ubiquitous deployment of immersive VR applications. Bachmann et al. [Hodgson et al., 2012] have been working with their portable immersive virtual environment system that utilizes IMUs placed on the feet and head. They use zero-velocity updates to derive nearly accurate positions and orientations from the sensors. In outdoor applications, a GPS is used for position tracking, and an ultrasonic transducer is used to plot the landscape in front of the user to create redirected walking paths and prevent the user from walking into obstacles.

This timeline embodies VR evolution through limitation. The standardized need to render and interact with a virtual 3D model evolved slowly but steadily over time. The concept of interacting with a virtual entity (3D models, environments, etc.) with real-time (60 FPS or higher) feedback is the basis of all VR experience.

### 2.1.2 What constitutes a VR experience?

The key elements in experiencing VR are a virtual environment, immersion, sensory feedback and interactivity.

#### 2.1.2.1 Virtual Environment

A virtual environment (VE) is the content and the subject matter of any virtual experience. It comprises of virtual entities (objects) and their descriptions. A VE 'capitalizes upon natural aspects of human perception by extending visual information in three spatial dimensions,' 'may supplement this information with other stimuli and temporal changes,' and 'enables the user to interact with the displayed data' [Wilson, 1999]. VEs offer a new inexpensive communication medium for human machine interaction. For example teleoperation tasks, such as in a laparoscopic surgical simulation, requiring coordinated control of the viewing position benefit from a VE interface as opposed to physically recreating a surgical simulation. VEs are considered a communication medium that has broad applications ranging from education and training to exploratory data analysis/visualization to entertainment. Furthermore, VEs are an essential tool in psychophysical, physiological, and cognitive science research, providing these fields with the backdrop to conduct experiments.

*Definition: Virtual environments are a description of a collection of objects in a virtual space and the rules and relationships governing those objects.*

#### 2.1.2.2 Immersion

Part of having a virtual experience demands the user being *immersed* via VR apparatus into an alternate reality. In general terms, *immersion* refers to a state of mind, a temporary suspension of disbelief which allows a user to move at will from real to virtual and vice versa. Good novelists exploit this fact to pull readers into their story. But none of this immersion is direct and is often presented from a third person point of view. In VR, however, the effect of entering an alternate reality is physical rather than being purely mental. For example, the process of putting on a HMD physically separates the peripheral vision of a user from the real to the virtual. A VR experience typically comprises both forms (physical and mental) of immersion. The VR community simply refers to mental immersion as *presence*. The terms *immersion* and *presence* are often confused and interchangeably used but Mel Slater [Slater, 2003] defines the terms as follows:

- *Immersion refers to the objective level of sensory fidelity a VR system provides.*
- *Presence refers to a user's subjective psychological response to a VR system.*

#### 2.1.2.3 Sensory Feedback

VR as a medium allows its participants to experience an embodied perspective [Sherman and Craig, 2002]. For example, in a flight simulator, the user embodies a virtual flight through direct control of a virtual cockpit. In order to elicit a perfectly immersed virtual cockpit, the *VR system* needs to track the user's head gaze and synchronize the ego-centric perspective to match the user's head gaze. This is a form of sensory feedback by a VR system. Sensory feedback is essential to VR and a VR system provides direct sensory feedback to the user based on their physical position [Figure 2.2]. The most predominant form of sensory feedback is visual, but there are other VR experiences that are based exclusively on haptic (touch) and aural (spatial audio) experiences. With regards to the scope of this dissertation, we will be discussing only visual sensory feedback.

*Definition: A VR system is an integrated collection of hardware, software and content assembled for producing VR experience.*

*Definition: Position tracking is the sensing of the position (and/or orientation) of an object in the physical world.*

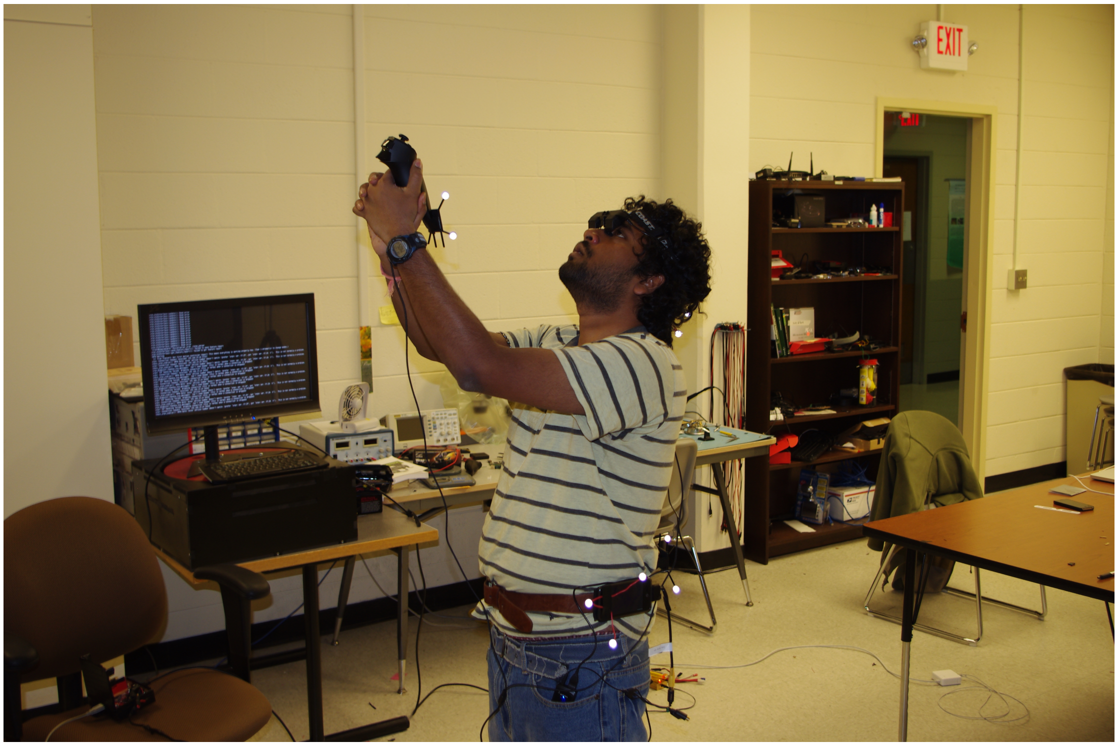


Figure 2.2: This is an example of a real-time position tracking using a five camera OptiTrack system (Flex 3 cameras) with retro-reflective markers being tracked at 100 FPS. This picture is courtesy of the Virtual Experiences Lab at UGA.

#### 2.1.2.4 Interactivity

A VR experience is authentic only when the user feedback loop [Sherman and Craig, 2002] is closed. In other words, when immersed inside a VE, the user should be able to interact with the VE and the VE should respond appropriately. Virtual experiences are associated with the ability to interact with the VE by changing locations, picking up objects and manipulating them, and closely following physical reality. There are many forms of interactions that contextually vary depending on the simulation subject matter. For example in a flight simulator, flipping the switches on the control panel of the virtual cockpit makes logical sense and should be interactive as part of the flight simulation virtual experience.

## 2.2 Ubiquitous VR design

The vision of ubiquitous computing in Mark Weiser's words [Weiser, 1994] is that 'a good tool is an invisible tool. By invisible, I mean that the tool does not intrude on your consciousness; you focus on the task, not the tool.' For VR systems to achieve such invisibility as described by Mark Weiser, the number of hardware (wearable) components has to be minimized so that the VR users can focus better on tasks. In 1991, it was quoted [Pausch, 1991a] that 'the field of virtual reality research is in its infancy, and will benefit greatly from putting the technology into as many researchers' hands as possible.' This marked an important shift in the conceptualization of VR system design with a focus on minimalism and the idea of using off-the-shelf hardware components to build an inexpensive VR system that would be highly accessible and affordable to users and researchers.

### 2.2.1 A brief history of ubiquitous VR system design

With an increased focus on motion-based and natural interfaces, the gaming industry has created a wide variety of readily accessible, off-the-shelf virtual reality equipment. This off-the-shelf equipment has vastly reduced the barriers of entry into immersive VR development, reduced costs in the virtual reality industry, and increased the ubiquity of virtual reality devices. While this trend has received much attention [Lee, 2008; Wingrave et al., 2010], it has a humble begining with Randy Pausch's initial effort back in 1991 [Pausch, 1991a].

Pausch's 'Five dollar a day' VR system was built using an 80386 IBM-PC$^{TM}$, a Polhemus 3Space Isotrak$^{TM}$, two Reflection Technology Private Eye$^{TM}$ displays, and a Mattel Power Glove$^{TM}$. At the time, the entire system cost less than $5000. The system displays could render monochrome wireframe of virtual objects at 720x280 spatial resolution. Pausch's work focused on offering a seamless VR experience rather than focusing on high resolution graphics and sterepscopic displays. Pausch quoted 'low-latency interaction is significantly more important than high-quality graphics or stereoscopy' [Pausch, 1991a]. Pausch's work revealed the importance of user experience and what really matters to the users in terms of having a consistent VR experience. Another important aspect of Pausch's work is accessibility and its redesign of VR systems so that they can be easily democratized. Pausch said 'the field of virtual reality research is in its infancy, and will benefit greatly from putting the technology into as many researchers' hands as possible' [Pausch, 1991a].

In order to design a universally accessible VR platform that offers seamless experience to users, we need to evaluate each individual components; namely, displays, user input schematics, and VR software. Pausch started with the evaluation of HMDs and stationary displays and their respective impacts on user performance [Pausch et al., 1993]. To simplify the study design, Pausch merely compared a head-tracked versus non-head-tracked camera controlled searching task in a virtual room. Pausch found that head tracking reduced task completion time by allowing the subjects to build a better internal representation of the environment.

Building on Pausch's early works, we conceptualized a new framework of collaborative computing in 2011 called the Ubiquitous Collaborative Activity Virtual Environment (UCAVE) [Basu et al., 2012a]. UCAVEs are portable immersive virtual environments that leverage mobile communication platforms, motion trackers, and displays to facilitate adhoc virtual collaboration.

Following our UCAVE framework, Anthony Steed published his work on design and implementation of a smartphone based VR system in 2013 [Steed and Julier, 2013]. In this work Steed described the development of a HMD-based VR system that is integrated into an iPhone-based platform. Steed's design of the system is novel in that it exploits the iPhone itself as an unseen touch controller. Steed's main implementation challenge was to align the two different IMU sensors; one from the smartphone and the other from the Freespace head tracker. Given that there we no external frame of reference to utilize, the user interface had to be adapted as discrepancies in yaw between the two sensors rapidly grew. To overcome these limitations, Steed introduced two mechanisms: a gesture to automatically realign the coordinate systems crudely, and a clutch to manually realign them precisely. Steed's system can operate at 60Hz for VEs with a few thousand polygons and latency is acceptable at approximately 100ms.

The limitation of different IMU sensor registration was resolved in our following work introducing a wearable electromagnetic (e-m), six degrees of freedom (6-DOF) single hand (position and orientation) tracking user interface that is inexpensive and portable [Basu et al., 2012b]. The e-m tracker was integrated successfully with our UCAVE framework. The e-m tracker provides a single frame of co-ordinate reference thereby offering fully untethered and self-contained configuration. The e-m tracker does not track user position in real world, which is not a mandatory requirement towards seamless VR experience.

At the same time, Judy Vance published her work on the potential of low-cost VR equipment [Lu[1] et al.] delving into various combinatorial feasibility analysis of consumer-grade video-gaming hardware such as Razer Hydra, Wiimote, and Microsoft Kinect. Vance's findings are, that in addition to providing 3D motion tracking, having analog controls and buttons are useful to create a more fluid interface for users.

Following the previous work, Suma et al. published his work on a multi-user VR platform [Thomas et al., 2014a]. Suma argued that factors such as poor accessibility, lack of multi-user deployment capability, dependence on external infrastructure to render and track, and the amount of time to put all these factors together restrict ubiquitous deployment of immersive VR experiences. Suma's MuVR platform offers to solve all logistical hindrances in deploying immersive VR experiences. Suma's prototype is similar to our UCAVE prototype [Basu et al., 2012b] with the difference of Oculus Rift DK1 dev kit as the HMD and the smartphone device being attached to the hips using a wearable harness. Suma's proposed system pushes the ideology of ubiquitous, immersive VR setup in the right direction by conceptualizing a modular setup towards democratized VR design.

In 2015, Ponto et al. introduced DSCVR [Ponto et al., 2015], a commodity hybrid VR system. Ponto's work presents design considerations, specifications, and observations in building DSCVR, a new effort in building a fully democratized CAVE [Cruz-Neira et al., 1992] like setup using commodity grade technology. Even though Ponto's work is not directly related to mobile, ubiquitous VR design, it follows a similar trend in that it is an attempt to democratize VR technology.

## 2.3 Current trends in ubiquitous VR

The ubiquitous nature of computer graphics workstations capable of driving complex real-time graphics, three-dimensional displays with higher frame rates and overall cost effectiveness and miniaturization of hardware resources are some of the key reasons behind the current push toward modern VR systems. 3D displays and VR systems existed before but the paradigm shift occured with the advent of smartphones and the app store. For example, the earlier flight-simulators such as the VCASS [Kocian, 1977] had significant graphics capability but have been expensive in deployment and required high maintenance to upkeep. Flight simulators are generally developed keeping in mind a very specific application such as training for particular military plane. They need to be programmed and micro coded in an assembly level language to reduce the overall graphics and CPU cycles required. This limits the code maintainability and further restricts potential upgrades both in terms of software and hardware. A majority of such systems such as VCASS are proprietary and thus are limited to a specialized class of users such as the military.

In the last decade, personal computing has evolved to provide higher accessibility and to provide an entry pathway to a larger domain of users who can contribute and open up other potential domains such as Education and Public Health. In contrast to their predecessors, current VR systems are much more efficient in design and performance, yet there is a fundamental lack of knowledge as to how and why users react to immersive VR in the way they do. With the introduction of mobile VR systems into the foray, we can understand the usability aspects of users engaging with VR and its content better than before. More features in VR technology does not correlate with better VR experiences. With the continued advancement of hardware, the VR community has reached a certain threshold where more insight in user analytics is required.

# Chapter 3

# Ubiquitous Collaborative VR - The Framework

> *"Research is what I'm doing when I don't know what I'm doing."*
>
> — Wernher Von Braun

Part of this work has been published as a paper in the proceedings of the ACM 2012 conference on Computer Supported Cooperative Work and in the 2012 IEEE symposium on 3D User Interfaces.

**Relevance to dissertation**

This chapter presents a collaborative framework called the Ubiquitous Collaborative Activity Virtual Environment (UCAVE) to enable deployment of virtual experiences using smartphone technology. The UCAVE framework lays the foundation for ubiquitous VR computing and becomes a template for the VR community to follow.

## 3.1 Introduction

We introduce a new paradigm of collaborative computing called the UCAVE. We envision UCAVEs to be portable immersive virtual environments that leverage mobile communication platforms, motion trackers, and displays to facilitate ad-hoc virtual collaboration. In this chapter, we discuss design criteria and research challenges for UCAVEs.

Collaborative virtual environments (CVEs) enable spatially distributed users to work together on shared tasks in a real-time interactive virtual environment. There exist a variety of CVE interfaces but researchers such as Hindmarsh et al., have argued that immersive interfaces yield better opportunity for collaboration [Hindmarsh et al., 2000] than non-immersive interfaces. Immersion inside a VE is generally difficult to achieve. The amount of effort to achieve full immersion relies on controlled laboratory setting which ultimately hinders large scale ubiquitous deployment [Bowers et al., 1996; Hindmarsh et al., 2000]. An immersive interface to a CVE includes a HMD technology with tracked avatar embodiment. A good example of an immersive interface would be DiVE [Benford et al., 2001]. On the other hand a non-immersive interface includes fixed planar displays with indirect input schematics such as keyboard and mouse. Even though, non immersive interfaces are standardized, when it comes to avatar control mechanism they can be confusing and ultimately counter productive [Hindmarsh et al., 2000]. However, the practical reality of immersive interfaces includes high cost, visual quality tradeoffs, extensive setup, user encumbrance, and limited deployment possibilities.

The UCAVE concept presented here aims to validate immersive interfaces as a choice that is dictated by application requirements and not by logistical limitations.

## 3.2 Background

The underlying technology required to make UCAVEs possible stems from early CVE research. In DARPA's SIMNET system designed for battlefield simulation, soldiers could join into highly complex 'war games' and other training simulations from sites around the country. Users in the original SIMNET were rendered as tank avatars, but later were rendered as human-form avatars through human body tracking [Pratt et al., 1994]. The MASSIVE and CAVERN systems share more similarity to the UCAVE, focusing on issues for collaborative social interactions using human avatars [Greenhalgh and Benford, 1995; Leigh et al., 1997]. MASSIVE and SIMNET were the ancestors of the highly successful Second Life, a massively multiplayer simulation [Macedonia, 2007]. The primary difference is that while MASSIVE and SIMNET were expensive research platforms, Second Life is a consumer level product. Its wide availability, customizability, and low cost (free to access) are the keys to its broad distribution. The UCAVE concept shares these characteristics by leveraging commodity mobile devices in a unique immersive configuration, thereyby enabling broad distribution of the benefits of CVEs to the general public. Personal digital assistants (PDAs) and palmtop computers have been employed in VEs as interaction devices or displays for a number of years [Fitzmaurice et al., 1993]. Highly relevant to the current work is the use of smart phones to control avatars [Gutiérrez et al., 2004]. The PDA has also been used for locomotion about a VE [Watsen et al., 1999], as a shared whiteboard between virtual reality users [Farella et al., 2003], and as a "magic lens", showing an enhanced view of the VE [Miguel et al., 2007].

A few limiting factors in earlier works were that the devices themselves were largely incapable of rendering a complex 3D VE, did not have powerful processors, had limited sensing capabilities, and had limited wide-area communication bandwidth. Modern smart-phones such as Apple Computer's iPhone and Motorola's Droid series have substantial graphics and CPU components, storage, and sensing capabilities. These devices are capable of supporting the paradigm shift from laboratory and personal computer based CVEs to mobile phone based UCAVEs.

## 3.3 UCAVE benefits

Hindmarsh et al. raised a number of concerns pertaining to what would typically be called a non-immersive CVE interface (an ordinary keyboard, mouse, monitor configuration) [Hindmarsh et al., 2000]. These were:

- The horizontal field of view of the display was limited, causing difficulty observing spatial references of others while simultaneously observing the referenced object (source and target).
- Actions were not always reflected by user embodiments, which can also be extended to include both virtual actions and real world actions (i.e., a user disengaging from the CVE interface)
- Navigation of the CVE was clumsy, owing to, amongst other things, the lack of an intuitive interface for navigation
- Parallel actions were not supported, such as moving an object and changing viewpoint simultaneously.

Hindmarsh et al suggested that an immersive interface (a tracked HMD with multiple tracked position sensors) could address these issues, but argued against an immersive interface because of logistical issues of cost, robustness, and setup difficulties [Hindmarsh et al., 2000]. The UCAVE aims to make the benefits of immersion accessible by reducing these logistical issues. *It should support immersive interaction, but not at the expense of user mobility or ease of use*. In other words, it should provide the expected affordances of a conventional immersive CVE interface: natural interactive viewpoint and avatar control, but be able to be carried around by the user and immediately deployed. While on its surface the principle is sound, immersion, mobility and ease of use are often conflicting, and thus design tradeoffs must be made.

## 3.4 UCAVE architecture

A general UCAVE architecture is shown in [Figure:3.1]. The smart phone (or similar handheld computing device) is the central core of the UCAVE architecture. Modern smart phones have a high-resolution display, a powerful system-on-chip (for interface, radio communication, graphics, and audio processing), and an array of sensors (e.g. touch-screen, accelerometers, gyroscopes, and magnetometers). The smart phone is connected to a head mounted audio-visual display. Additional body-worn sensors are incorporated as needed through personal area network technologies. When connected over a wide area network (i.e.. the Internet), remote users can join other UCAVEs, creating collaborative workspaces. Finally, at certain locations in the environment, external sensors may be available that provide additional capabilities to the user (e.g. a motion capture

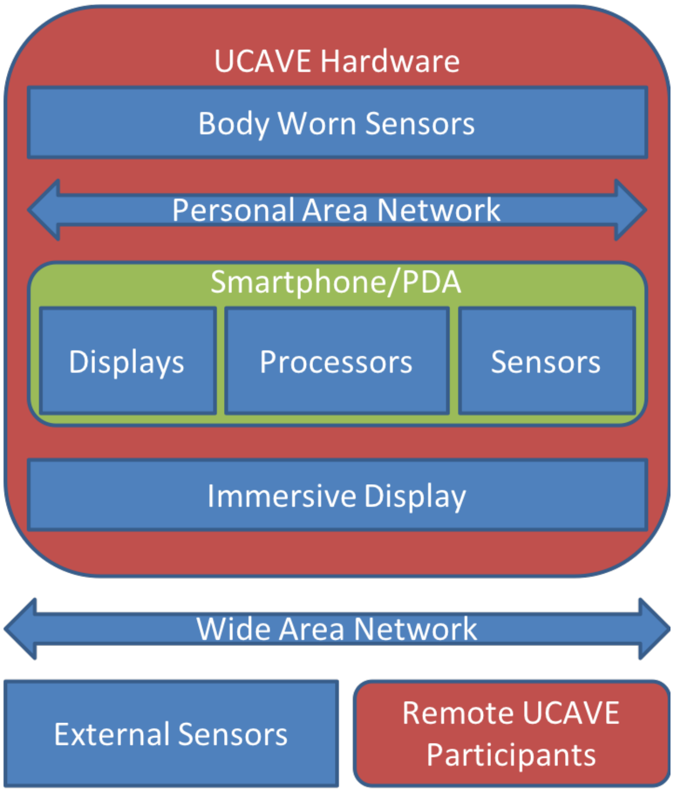


Figure 3.1: The UCAVE architecture.

system).

## 3.5 UCAVE prototype

In 1991, Randolph Pausch published a paper entitled "Virtual Reality on Five Dollars a Day" describing the design of a $5000 (USD) virtual reality (VR) interface; which, amortized over three years, was about five dollars a day [Pausch, 1991b]. To build such a low-cost system, off-the-shelf hardware was combined with creative engineering to form a makeshift, but complete, immersive 3DUI. The cost was a stark contrast to expensive commercial systems available during that time. More important than the price, however, was the possibility of immersive technology being available to vast numbers of designers and end- users, enabling immense creative efforts and sparking *a renaissance of VR*. Two decades later, this possibility is now rapidly becoming a reality. In this chapter, we present an evolution of this idea, a complete, immersive 3DUI for *one dollar a day*.

Enabling this evolution are low-cost consumer electronics devices that are mass-produced for entertainment purposes, yet are essentially the same technologies once reserved for VR applications, and often have as good or better performance than existing "professional" devices [Wingrave et al., 2010; Lee, 2008; Suma et al., 2011]. These consumer devices are thus viable alternatives for 3DUI designers, and have indeed been particularly popular for prototyping new systems [Hutson and Reiners, 2010; Gallo et al., 2008; LaViola Jr, 2008].

Building upon this idea, we have previously reported on the design of a mobile-VR system for immersive collaborative virtual environments [Basu et al., 2012a]. The goal was to design a low cost system that would allow a user to enter a shared virtual space from anywhere, with the immediacy of a phone-call. Our approach combined a networked smart phone device with its embedded motion sensors and a connected head-mounted-display (HMD). The effect was to produce a minimal virtual reality system that could be used within seconds of the user's desire to enter a shared virtual space.

The primary limitation of the previous design was that only immersive viewing (orientation only) was well supported. For hand position tracking, a mechanical, head-mounted, 3-degrees- of-freedom (DOF) tracker (constructed from the MadCatz Gametrak device) was provided, similar to [Koch and Witt, 2008]. While this approach was accurate, it had a limited range and was uncomfortable for the user. In this work, we present a design that addresses the challenge of immersive interaction and locomotion, without sacrificing the low-cost, portable design and that increases overall system performance.

## 3.6 Approaches to inexpensive mobile VR

Augmented reality (AR) researchers have been striving for mobile wearable technology, as the domain does not lend itself as well as VR to the constraints of small spaces. With respect to the current system, the most influential work has been Foxlin and Harrington's Weartrak, which used a see-through HMD and an acoustic-inertial tracker to obtain self-referenced, sourceless tracking [Foxlin and Harrington, 2000]. The inertial sensor tracked the HMD orientation to provide sourceless immersive viewing, while the acoustic sensor provided hand-position tracking in the reference frame of the HMD. This was an excellent approximation to the otherwise difficult problem of immersive hand tracking without an external tracking system. Others have addressed this problem using optical tracking. Piekarski and Smith used ARToolkit markers mounted on wireless data gloves that detected pinching gestures [Piekarski and Smith, 2006]. This approach had the advantage that a 6-DOF hand pose could be detected alongside gestures. Mistry et al developed Wear Ur World (now Sixth Sense) using a head-worn pico-projector and camera that tracks colored markers worn on the finger tips and mounted on objects [Mistry et al., 2009]. This approach provides very low user encumbrance. Beyond tracking, Avery et al presented a low-cost approach to AR using consumer level technology [Avery et al., 2005].

Low-cost VR has been emerging as a large segment of the VR market, as a result of the wide availability of low-cost displays and tracking systems originally designed for the entertainment sector. A number of companies make inexpensive HMDs for use with portable video devices (e.g. Vuzix, EMagin), and motion- controllers have become increasingly popular for gaming (e.g. Nintendo Wii Remote, Microsoft Kinect, Sony Playstation Move).

Furthermore, smart phones and similar mobile devices are available that have powerful processing, graphics, and display capabilities (e.g. Apple iPhone & iPod Touch). While the performance may lag behind that of traditional VR systems, they are rapidly improving in performance with GHz multi-core CPUs and dedicated GPUs. In fact, Olsen et al demonstrated the use of these devices as a stereoscopic HMD with custom optics [Olson et al., 2011].

Our contribution is to merge related work in portable, low-cost VR, providing a high degree of immersiveness and interactivity at a price that allows for ubiquitous deployment of such systems.

## 3.7 System

According to Pausch, the foundation of an immersive system consists of a tracked HMD supporting immersive viewing, a hand held or worn tracked device supporting immersive interaction, and a computer to integrate tracking and render the virtual world [Pausch, 1991b].

**Display**: A lightweight HMD (The Vuzix Wrap 920) is used for the display. The HMD has two independent 640 x 480 24-bit color liquid crystal displays (LCDs), and supports stereoscopic rendering via a side-by-side display format (in stereoscopic mode, each rendered view is 320 x 480 and is interpolated to 640 x 480). The aspect ratio is 4:3, with a 30deg diagonal field-of-view. While it has a low field-of-view and resolution, the lightweight (110g), battery powered (2 AA for 2 hours running time) design makes the Vuzix HMD well suited for a mobile display system. The Vuzix HMD was modified slightly by replacing the sunglasses- style mounting with an elastic band in order to more securely and comfortably bind the display to the wearer's head and provide more convenient mounting of tracking devices.

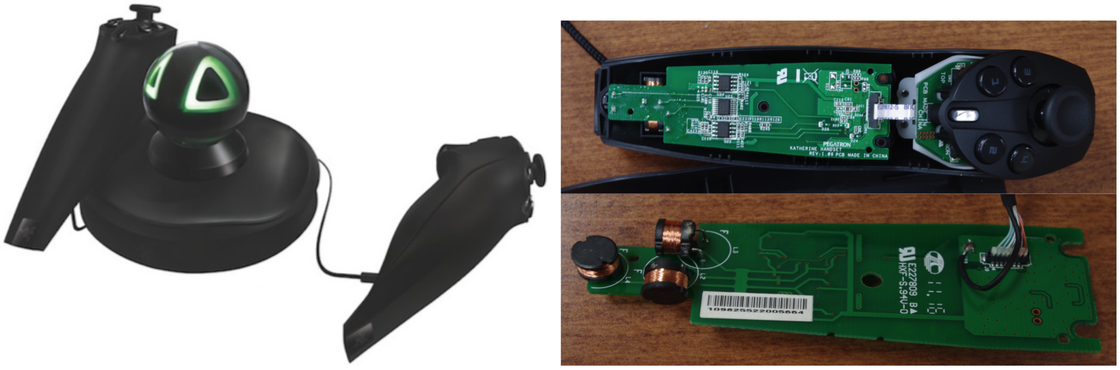


Figure 3.2: The Razer Hydra and its decomposition to remove the circuit board containing the magnetic sensing coils.

**Tracking and Interaction**: Two tracking and interaction devices are used. The first is the sensor system built into the iPod Touch 4g. This device has a 3-axis accelerometer (16-bit, -2.4 $g_n$ to 2.4 $g_n$), and a 3-axis gyroscope (16-bit, -2000 deg/s to 2000 deg/s). A filter is used to integrate accelerometer and gyroscope readings and produce an orientation that is correct about the axis of gravity. The Apple iOS Core Motion library performs this filtering and provides a unit-quaternion representing the orientation at 100Hz.

The second tracking system is the Razer Hydra. The Razer Hydra is the first mass-produced magnetic tracking system intended for the video game market. It provides 250Hz 3DOF position and orientation of two wired hand-held controllers, each of which has a joystick and 8 buttons. It is small [Figure 3.2], lightweight (800g), and powered through the USB system. The position and orientation computations are performed on device, and can be obtained through a free SDK from Sixense (developers of the Razer Hydra), or through a virtual reality peripheral network (VRPN) server developed by Ryan Plavik (https://github.com/rpavlik/razer-hydra-hid-protocol). We learned that the magnetic tracking sensor could be removed from the Razer Hydra controller, making it much smaller and lighter at a loss of the buttons and joystick [Figure 3.2].

**Computing**: Two mobile computers are used. The first is the Beagleboard XM single board computer. The Beagleboard XM includes a Texas Instruments DM3730 System-on-Chip (1GHz Arm Cortex A8 processor, 512MB memory, and PowerVR SGX530 graphics chip). It has interfaces for 4 USB devices, audio, S-Video, and HDMI. As the vast majority of consumer- level interaction devices (e.g. the Razer Hydra) have USB interfaces, the availability of powered USB connections was an important consideration. The Beagleboard XM can run the Linux, Android, or Windows CE operating systems. Linux was used in this work (Ubuntu 9.10).

The second computer is the iPod Touch 4g. It contains an Apple A4 System-on-Chip (800MHz Arm Cortex A8, PowerVR SGX540 GPU, 256MB memory), built-in WiFi and

Bluetooth networking, and has a proprietary connector that can be used to attach external devices including displays. The iPod Touch was primarily chosen because of its wide customer base (millions of devices), software distribution mechanism (Apple AppStore), impressive embedded sensors, and because it connects directly to the Vuzix HMD. Use of other smart-phones and platforms is possible, provided they can attach to the HMD. For example, the Beagleboard's s-video output could also drive the HMD.

Figure 3.3: (Left) A user within the low-cost, portable, immersive virtual environment outdoors. (Right) Components hidden under the shirt of the user on a belt: an electromagnetic tracking source, single board computer, and smart phone.

**Design**: As shown in Figure 3.3, the Razer Hydra source is mounted to the back of the belt. The iPod Touch is clipped to one side and connected to the HMD controller box. The Beagleboard is mounted to the other side and connected through USB to the Razer Hydra and a WiFi adapter. One of the two Razer Hydra pose sensors is separated from its controller body and attached to the HMD. The user holds the other controller. This design greatly increases immersion with respect to the previous design. The Razer Hydra provides robust 6-DOF pose tracking for the user's head and hand relative to the hips of the user. The iPod Touch inertial sensors track the orientation of the hips, and thus no functionality is lost. Furthermore, the head and hand tracking now have the same frame of reference (the hips) and tracking performance characteristics, which is important for maintaining consistency (although we introduce a latency discrepancy when the hips are moving, as discussed in section 4).

Mounting the iPod Touch at the hip, instead of the head, allows the use of several common locomotion metaphors. In addition to moving by pointing or with the joystick, the accelerometer can be used to detect motion. While double integration of accelerometry is theoretically possible, numerical error accumulation makes this infeasible. However, footfalls can be detected reliably (see Section 4), allowing locomotion by walking in place or real walking (provided space is available). All of these techniques offer only relative motion. Absolute motion currently requires an external system, e.g. GPS or fiducial tracking markers.

An ad-hoc WiFi network connects the Beagleboard and iPod Touch. Data from the Razer Hydra is read by software on the Beagleboard and transmitted using the VRPN library to the iPod Touch. The iPod then converts the incoming pose data for the head and hand into its own reference frame (as obtained from its inertial sensors).

## 3.8 Performance characteristics

To test the performance of the user tracking and devices, we conducted comparisons with a 5-camera NaturalPoint Optitrack optical tracking system. This tracker provides 6-DOF

Table 3.1: Average frames per second for test scene by device and number of virtual human avatars (11200 polygons each) in the scene. *The hardware is limited to 60 frames per second.

| Avatars | iPod Touch 4g | iPhone 4S |
|---|---|---|
| 1 | 60* | 60* |
| 2 | 41 | 60* |
| 4 | 24 | 48 |
| 8 | 13 | 26 |

pose measurements of rigid constellations of reflective infrared spheres at a 100Hz update rate. Within the 3m x 3m x 3m tracking volume it has excellent accuracy (< 1cm), resolution (< 1mm), and latency (10ms). All data was collected on the iPod Touch, which sampled at 60Hz (its maximum frame rate for 3D applications). No filtering was performed on the data. All objects (the iPod touch, Razer Hydra source, head sensor, and wand sensor) were tracked by the Optitrack system.

For the first test, we compared [Figure 3.4] the orientation measured by the iPod Touch inertial sensors to that measured by the Optitrack system. We collected a 30 second sample of rapidly swinging orientation motions from both the iPod Touch and an Optitrack sensor rigidly attached to the iPod (timestamps were recorded on the iPod touch as data arrived from the Optitrack system over VRPN). We converted the quaternion obtained from each tracking system to an axis-angle notation and used the angle as the comparison metric. We noticed a substantial latency from the iPod Touch orientation sensor with respect to the Optitrack sensor. By time shifting the OptiTrack data until the error between the two sensors was minimized, we determined this latency to be

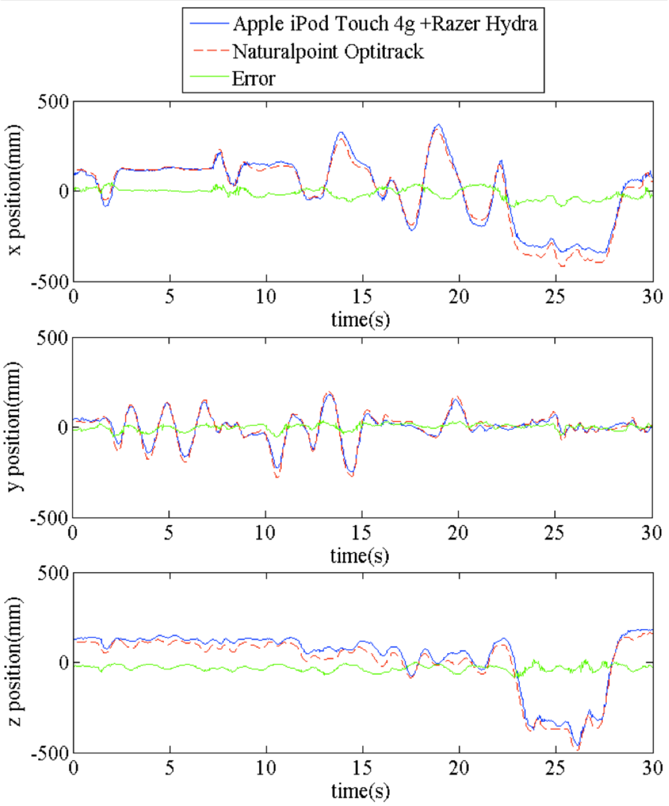


Figure 3.4: X, Y, and Z positions measured by the Apple iPod Touch 4g + Razer Hydra and the NaturalPoint Optitrack System.

41ms (this is in addition to Optitrack and network latencies). The average absolute error between the two measurements was approximately 4 degrees.

For the second test, we compared [Figure 3.4] the position accuracy of our hybrid inertial-magnetic tracking system to the NaturalPoint Optitrack system. The average absolute errors were 24.6mm, 13.4mm, and 13.5mm for the x (left), y (up), and z (out) axes respectively. Latency, in this case, was difficult to determine, as it is a combination of the two tracking systems employed; however, at times there appeared to be no latency between the two systems. This can be explained by the combination of the systems. The Razer Hydra has a marketed 4ms latency. This is less than the 10ms latency of the Naturalpoint Optitrack system. Our measured latency of the iPod touch inertial sensor is at least 41ms. Thus, it depends on which one is currently varying as to what latency will be perceived. The two most important components, head and hand tracking, are both measured with the low-latency Razer Hydra.

For the last test, we measured the rendering performance of the system. A test scene was composed in the Unity 3D game engine. Unity 3D was chosen for convenience, and could be replaced by a free alternative such as Ogre 3D (as was used in our earlier work). The scene consisted of a number of articulated virtual humans and was indicative of the environments that we envisioned the system would be used for: social, collaborative environments. The virtual humans were obtained from www.evolver.com and were each 11200 triangles. To test, we varied the number of virtual humans visible in the window. The environment was rendered in a side-by-side viewing configuration for the left and right eyes (as needed by the HMD). For comparison, we also measure frame rates for the more powerful iPhone 4s (Apple A5, 800MHz Dual Core). The iPod Touch 4g performance was about half that of the iPhone 4s [Table 3.1]. Interactive frame rates were achieved in all cases, although the eight-avatar case for the iPod Touch 4g was only marginally acceptable at 13 frames per second.

## 3.9 Discussion

The performance experiments addressed areas of concern related to the inexpensive approach. First, we showed that the iPod Touch 4g inertial sensor was capable of accurately tracking the orientation of the user. The errors were low (approximately 4 degrees) and only accumulated about the axis of gravity. However, it did have a high latency (approximately 41ms). This was a concern with the previous head-mounted design, as rendering was directly coupled to the tracking system. In the new approach, however, latency in the inertial tracker is indirectly coupled to the magnetic tracker, only affecting the view when the hips are rotated. Thus, if hip rotation is infrequent for an application, the latency will not be a large source of concern.

The purpose of the magnetic tracker was to enable body-centric position tracking. In this regard, the performance of the system was exceptional. Magnetic tracking is well suited for body centric interaction, particularly when the magnetic source is mounted to the body. This alleviates some of the primary causes of error associated with magnetic tracking, namely distance from the source (the source travels with the user) and magnetic field distortions (the body does not distort magnetic fields). In fact, we noted during the experiments that the Optitrack system frequently lost track, and occasionally flipped orientations, making it the less robust of the two tracking systems for body-centric tracking. The Razer Hydra, in particular, is a high quality product for its price, and the ability to remove just the magnetic field sensor from the body of the wand makes it even more flexible.

Lastly, we note that the rendering performance of the iPod Touch 4g was adequate for many VR systems. Also, we found that smart phone performance is exponentially increasing with each generation. It is likely that rendering performance will not be a major issue for future generations of this concept.

### 3.9.1 Limitations

There are some limitations to the tracking approach. First, the system does not support crouching or climbing, because it technically cannot detect the height of the user's hips above the ground. We could incorporate additional magnetic sensors on the feet and torso. This would enable crouching to be detected, and would improve locomotion.

Another related limitation is that finger tracking is not supported. While inexpensive data-gloves were examined for this system (e.g. P5 Glove and the Nintendo PowerGlove), these were not of sufficient quality to incorporate. Low cost optical tracking approaches show promise in this area.

The largest remaining concern is the lack of an inexpensive large field-of-view head-mounted display. The Vuzix VR920 has reasonable visual quality, and its lightweight design makes it comfortable to wear for extended time, but its low field of view makes achieving a sense of presence difficult. For this reason, we did not try to block out the real world [Figure 3.3]. Thus, current applications will likely be oriented towards social gatherings and entertainment rather than those relying on high presence such as exposure therapy.

### 3.9.2 Research Questions and Challenges

The nature of an inexpensive, portable, untethered VR system poses intriguing new research questions and challenges, specifically related to the idea that VR or 3DUI experiences are likely to occur in uncontrolled environments. Given that VR is concerned with the virtual world, the overarching question is *"what do we do with the real world?"*

**Effectiveness & Distraction**: Can we build VEs or 3DUIs that are effective, despite the often-unpredictable distractions present in the real world (e.g., a knock on the door, a blaring ambulance driving past, or drops of rain when outdoors)? Furthermore, how do we evaluate the effectiveness of VEs or 3DUIs in uncontrolled environments? Traditional measures of presence may not be appropriate for VEs where distraction is the norm.

**Hiding Reality**: Should portable VR or 3DUI systems like the one presented here block out the outside world? For example, redirected walking [Razzaque et al., 2001] and other techniques based on perceptual illusions could be used to minimize the chance the user collides with a real wall. Similarly, if it starts to rain in the real world, the system could generate rain in the virtual world to minimize distraction from the unexpected external stimuli.

**Leveraging Reality**: Alternatively, could characteristics of the real world be used to improve the VE or 3DUI? For example, if a map of the user's external environment were available, one could automatically align the VE with the real world (e.g., align real and virtual walls) to provide passive haptic feedback. Similarly, if the virtual experience takes place in a rainy outdoor environment, the user could enter the VE while standing outdoors in the rain.

## 3.10 Conclusions

With the low cost system described in this chapter, the monetary barrier to entry in immersive VR is all but eliminated. For less than the price of a mid-range television (particularly if the user already has a smart phone), a user may interact in immersive virtual worlds. It is possible that in the near future, VR will become ubiquitous, but for that to occur, mass-appeal applications are needed. Our hope is that the approach presented in this chapter could serve as a catalyst for creating such applications.

Our future work with this system is currently targeted towards large-scale collaborative interactions for "second-class" applications that cannot afford large-scale virtual reality installations, such as education and entertainment. With the current design it is possible to deploy hundreds of immersive systems in places that were once never thought viable.

# Chapter 4

# User Study I - The Ergonomic Impact of a Perceived Tether in Ubiquitous Immersive VR

> *"It is only through failure and through experiment that we learn and grow."*
>
> — Isaac Stern

**Relevance to dissertation**

This chapter presents our pilot study conducted from 2012 to 2013 reflecting upon strategies, general usability, and findings of ubiquitously deployed immersive spatial navigation experiences with particular attention paid to ergonomic factors such as being tethered versus untethered.

## 4.1 Background and motivation

As the proliferation of commercial hardware continues to make immersive VR systems increasingly accessible and designers and engineers continue to advance the possibilities of immersive VR experiences, the ergonomics of such VR systems must be further studied. We designed a user study to measure the difference in user performance between an immersive VR experience deployed using a wireless, untethered VR system and an immersive VR experience deployed with a tether attached to the same VR system. This tether was, in fact, a "fake" (12 ft.) USB cable that remained unattached from any computer ports, despite being attached to the VR system. We then examined the differences between untethered and tethered participants' successful completion time of a virtual maze to see if there was a significant difference. We used our prior ubiquitous VR system to implement the User Study I [Basu et al., 2012b].

The goal of our ubiquitous VR system is to deploy immersive virtual experiences without the need for an elaborate infrastructure. Our current experimental design involves leveraging science fiction media as a tie-in to the virtual reality demonstration. This is a concept that has historical validity for improving the VR experience [Pausch et al., 1996], but seems to be missing in the vast majority of 3DUI and VR research. Our vision is that studies conducted within the framework that we designed for this work will ultimately yield insights into many persistent issues in 3DUI and VR research, because of the ease of use, scalability, and standardization that is possible with the UCAVE. The rationale for this is that conducting extensive research on immersive interfaces is very difficult when expensive, highly specialized technology is employed. It is unheard of for more than a few immersive setups to be deployed simultaneously in research. With the UCAVE, potentially hundreds of equivalent immersive experiences can be deployed to users for the equipment cost of, for example, a single CAVE [Cruz-Neira et al., 1993]. There is merit in this approach, especially for education and training in classrooms that are currently underserved by VR research.

## 4.2 Hardware and software design

Our early ubiquitous VR system design [see chapter 3] had issues with the tracking approach as it used one of the two available Razer Hydra sensors to track the head of the user relative to the body of the user. This provided low-latency (4 ms) tracking of the head pose (6 degrees-of-freedom) relative to the body. The body-orientation, with respect to the world reference frame, was then tracked by the inertial measurement sensors that were embedded within the smartphone. The issue with this approach turned out to be that the quality of magnetic tracking is highly dependent on distance. Taller users had the source much farther away from the sensor, yielding inaccuracies and jitter. Furthermore, head pose tracking had two sources of latency: that from the smartphone and that from the magnetic tracker. This resulted in inconsistent tracking. The second major issue was the quality of the HMD. The particular HMD used (Vuzix Wrap 920) was designed for entertainment in private, not for immersive interaction [Vuzix, 2007]. It was lightweight and inexpensive, which were desirable, but ultimately the visual quality and low field of view (30 degrees diagonal) greatly limited the application. Furthermore, the HMD introduced a noticeable latency when rendering the VE. Coupled together, this would have made it very difficult to use in a practical experiment. Based on these issues, we proceeded to redesign our ubiquitous VR system.

We designed a head-mounted apparatus to hold a stereoscopic smartphone viewer built from ski goggles [VRGeeks, 2012] [see Figure 4.1]. Our viewer uses two 10x aspheric lenses derived from jeweler's eye loupes. It is designed specifically to be used with iPhone 4/5 and iPod Touch 4/5 screens, which have a standard 2-inch width across models, and 3 or 3.5 inch height (depending on the model). The resolution is fixed at 326dpi. This results in a 960 x 480 or 1136 x 640 resolution. While this is technically lower (per eye) than the resolution of the Vuzix HMD (640 x 480), the color quality is higher, the latency is not present, and two wires and a battery are removed from the system. Furthermore, the Vuzix HMD required a split screen stereoscopic signal, effectively halving the resolution. Thus, the visual quality was superior on the smartphone-based HMD in stereoscopic viewing. We also introduced Raspberry Pi as our single board computer [RaspberryPi, 2013]. Finally we made changes to our tracking hierarchy to resolve inconsistencies in tracking the sensors. The 3D Matrix$^{TM}$ maze experience was developed using the Unity game engine.

## 4.3 Study design

**Null hypothesis**: *There isn't a significant impact on successful completion time of the maze under the presence of a 'fake' USB tether (perceived tether).*

**Alternate hypothesis**: *There is a significant impact on successful completion time of the maze under the presence of a 'fake' USB tether (perceived tether).*

Figure 4.1: The UCAVE setup used for deploying Study I.

The study was designed to compare the effect of 'perceived' tethering on users' time of completion of a decently complicated maze.

It is important for a ubiquitous VR system to offer reliable access to immersive VR content. Thus, we needed an application that highlighted 'ubiquitous immersive interaction' to the general public. Popular science fiction seemed like an appropriate source to draw from for this purpose. The Matrix$^{TM}$ film series is a contemporary science fiction work that envisions a futuristic world with fully immersive technology similar to that envisioned by Ivan Sutherland's Ultimate Display [Sutherland, 1965]. As one of the most popular film franchises in recent history, and with its focus on immersive topics, we decided to model our experience loosely after the concept of 'entering the matrix' (entering the VR world from the real world), where the user must then complete a task and 'get out' of the virtual world through a portal (a virtual telephone) [see Figure 4.2].

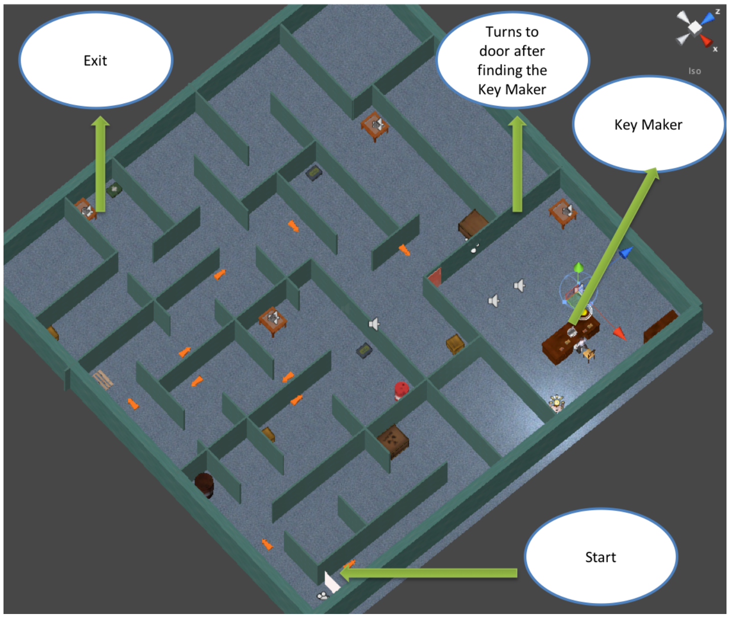


Figure 4.2: A bird's eye view of the maze design in Study I.

### 4.3.1 Tasks

At the start of the experience, the user puts on the head-mounted display, which is displaying the image from the smartphone camera. Then, they are 'plugged in' to the Matrix™, and the real world transitions to the virtual world (similarly to how it occurs in the film series). The benefits of having such a transition on presence have been previously studied by Steinicke et al. [Steinicke et al., 2009]. We put the subject into the shoes of the protagonist of the series, 'Neo'. The subject then has to find a missing person ('the key maker') inside the maze-like labyrinth. After finding the person, they are then trapped when 'a change is made to the matrix'. They then need to find their way out of the maze by locating a ringing telephone (3D sound). The audio source is continually played back at a given position in the maze and will attenuate over distance. The spread of the audio source is controlled by a logarithmic falloff curve. Once found, they transition out of the experience back to the augmented reality (AR) view [see Figure 4.3].

The theme of the experience masks what is otherwise a very typical test-bed for immersive interface experiments, a virtual 3D maze with visual and aural cues. However the film tie-in makes the experience compelling, especially for users who have seen the films and can relate to the content. The content of the maze has multiple unique landmarks spread throughout (various objects of different shapes and sizes) providing opportunities for the user to use strategy in order to solve the maze and find their way out. The 3D maze also involves accomplishing interactive tasks like opening a virtual door to get inside a room, responding to situations critically, picking up a virtual telephone etc. The control scheme was natural motion of the head and body, with the exception of locomotion, which was accomplished by means of the joystick on the hand-held wand. Interaction with the world was simplified as intersection between a virtual hand (motion matched to the hand-held wand position and orientation) and virtual objects, such that the user could "pick up the phone" or "open the door".

### 4.3.2 Measures

Data automatically recorded during the course of the maze navigation was used to measure the performance of each participant. For every session, we recorded, every 5 ms apart, the participant's spatial trajectory inside the maze along with orientation of gaze information. The data contained information retrieved and extracted from 38 participants with the following attributes: subject id, date, gender, age, 20/20 vision, videogaming experience index, treatment category, ethnicity, time to reach the room (secs), time to reach the exit (secs), total time taken inside the maze (secs), total turns (room) in degrees, total turns (phone) in degrees, total turns inside the maze in degrees, time to complete 2D maze (secs), relative simulator sickness score (low: 16; high: 160), and presence score (low: -21, high: +21). We used SPSS to conduct the analysis of the data.

Figure 4.3: Users' perspective inside the Study I maze in stereoscopy.

### 4.3.3 Population and Environment

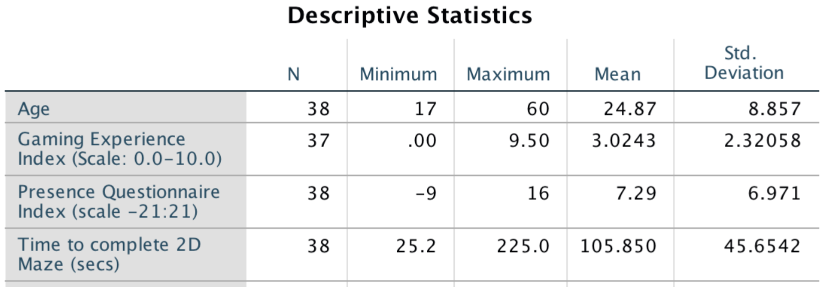
We obtained approval from University of Georgia's institutional review board to conduct the user study at various high-traffic, indoor, public locations on our campus. Over the course of a week, for a few hours a day, we recruited people passing by our demonstration booth [see Figure 4.4] to try the experience and provide feedback to us on various usability topics. We gathered quantitative data on task performance, simulator sickness, and presence. We tethered some users by a 'fake' USB cable to a host computer, to see if we would find substantial differences in how people interacted with the system, and their overall impressions of the system and experience. We collected background demographic data on participants including age, gender, prior game-playing experience and current gaming activities. For simulator sickness we used the Kennedy et al., Simulator Sickness Questionnaire [Kennedy et al., 1993] administered before and after the experience. For presence, we used the Steed, Usoh, Slater questionnaire from [Usoh et al., 2000]. In addition, we had users solve a 2D maze on paper and measured the time it took them to solve it. During the experience, we logged user position and orientation trajectories, and timed how long it took them to complete the two tasks (finding the Key Maker, and finding the exit). Finally, we asked users for comments on the experience and system.

## 4.4 Results

We have had 38 participants (Mean age: 24.87; SD: 8.857) complete the immersive VR experience in total [see Figure 4.5]. We had 28 (+4 dropped out) participants in the unteth-

Figure 4.4: A user participating in the Study I for usability and validation of our ubiquitous VR system [Basu et al., 2012b].

ered group (treatment category 1), and 10 participants in the tethered group (treatment category 2). More participants were in the untethered group because we were primarily aiming to formatively evaluate the UCAVE under ideal conditions, and so only every fourth person was recruited for the tethered condition. Four participants' data were discarded from the analysis because they did not complete the study (all from the untethered group). Three simply did not have the time to finish the experiment. The remaining participant reported a feeling of nausea and elected to stop the experiment. Participants who completed the maze spent an average of 145s (SD = 79s) to reach the Key Maker, and 221s (SD = 177s) to reach the exit. This indicates to us the difficulty of the task is reasonable,



**Descriptive Statistics**

| | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| Age | 38 | 17 | 60 | 24.87 | 8.857 |
| Gaming Experience Index (Scale: 0.0-10.0) | 37 | .00 | 9.50 | 3.0243 | 2.32058 |
| Presence Questionnaire Index (scale -21:21) | 38 | -9 | 16 | 7.29 | 6.971 |
| Time to complete 2D Maze (secs) | 38 | 25.2 | 225.0 | 105.850 | 45.6542 |

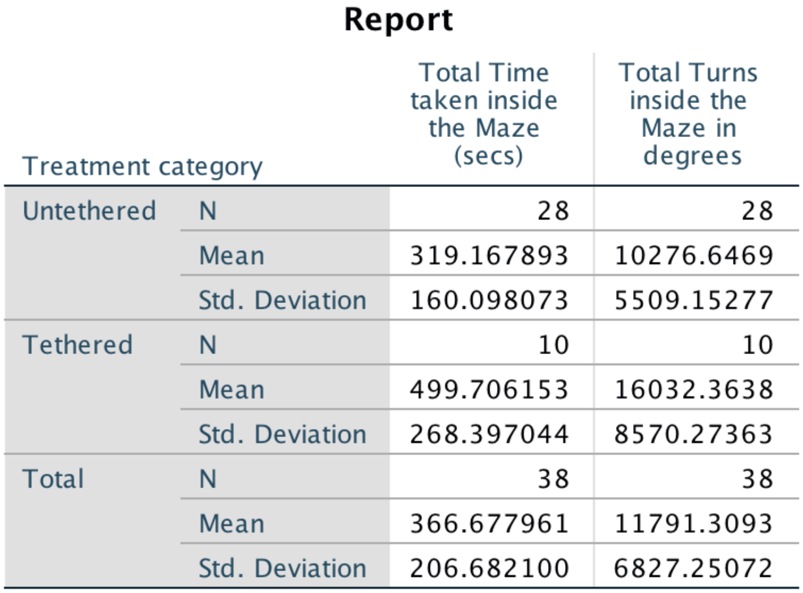
Figure 4.5: Descriptive statistics of within-subject metrics in User Study I.

and provides support for the level of usability of the system. This is particularly true, in that we did not provide any user training beyond an explanation of the joystick controls prior to the experience.

Within group (tethered versus untethered) descriptive statistics reveals that the mean total time taken inside the maze is lower (319.167 secs) for treatment category 1 (untethered) than for treatment category 2 (tethered) [see Figure 4.6]. We then proceeded with inferential statistics and conducted an independent samples t-test between the groups (tethered versus untethered). We see that there is significant group differences [see Figure 4.9].

## 4.5 Discussion

We *reject* our null hypothesis and we accept the alternate hypothesis. We found that the untethered group performed better overall in comparison to the tethered group participants. Overall self-reported presence was positive. Each of seven questions was on a scale



**Report**

| Treatment category | | Total Time taken inside the Maze (secs) | Total Turns inside the Maze in degrees |
|---|---|---|---|
| Untethered | N | 28 | 28 |
| | Mean | 319.167893 | 10276.6469 |
| | Std. Deviation | 160.098073 | 5509.15277 |
| Tethered | N | 10 | 10 |
| | Mean | 499.706153 | 16032.3638 |
| | Std. Deviation | 268.397044 | 8570.27363 |
| Total | N | 38 | 38 |
| | Mean | 366.677961 | 11791.3093 |
| | Std. Deviation | 206.682100 | 6827.25072 |

Figure 4.6: Descriptive statistics of performance metrics by group (tethered versus untethered) in User Study I.

from -3 (strongly disagree) to 3 (strongly agree). Counting only those who had an aggregate score of 14 or higher, indicating a high level of self-reported presence, we had 22 of the 38 participants who had high presence, and only 5 participants who had a negative aggregate score. Simulator sickness is a great concern, particularly for HMD-based VR systems. Aside from the one participant who did not complete the experience because of nausea, we did not observe a significant difference between pre and post experience simulator sickness scores. It is possible that users were not exposed to the virtual experience for long enough for significant effects to be observed.

**Additional findings**: Additionally, we observed a high level of interest in our ubiqui-

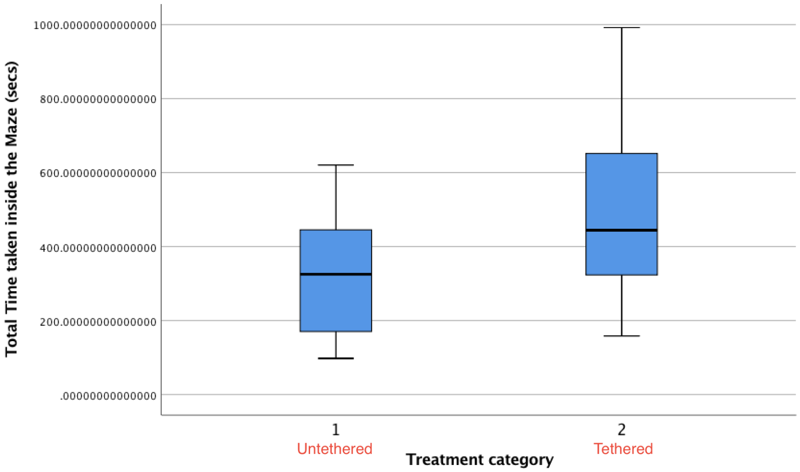


Figure 4.7: Boxplot showing total time taken inside the maze by group (tethered versus untethered) in User Study I.

tous VR system UCAVE [Basu et al., 2012b] by those participating, and in the crowds that often enclosed the participant when the system was in use. People are not accustomed to seeing virtual reality systems in public places, and had many questions for the experimenters. Most often, students wanted to learn more about how to build such systems, generating exposure for the VR and computer graphics course in our curriculum.

To summarize, in this study, we have described how to build an immersive virtual experience and deploy it beyond the controlled setting of a laboratory. We also measured the impact of becoming completely untethered on user performance while using ubiquitous VR systems. Having established the fact that being untethered in immersive VR is desirable, the next step is to examine environmental factors and its impact on immersive VR user performance.

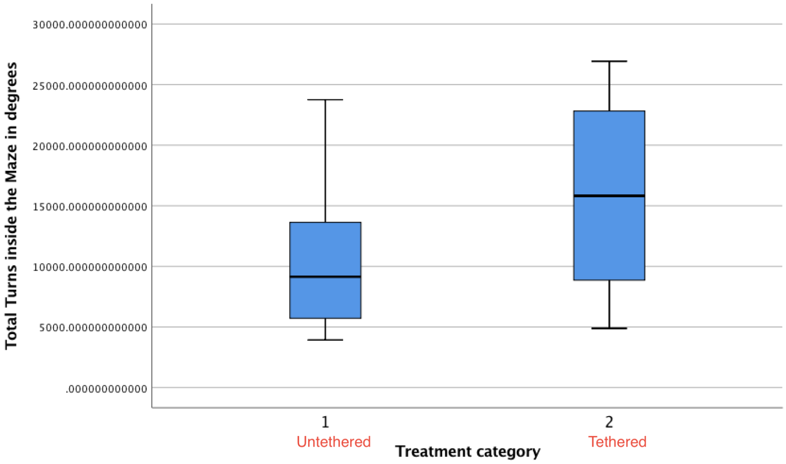
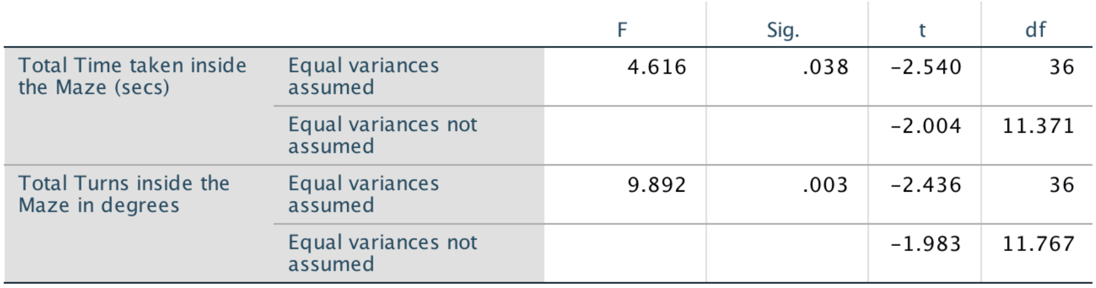


Figure 4.8: Boxplot showing total turns taken inside the maze by group (tethered versus untethered) in User Study I.

* * *



| | | F | Sig. | t | df |
|---|---|---|---|---|---|
| Total Time taken inside the Maze (secs) | Equal variances assumed | 4.616 | .038 | −2.540 | 36 |
| | Equal variances not assumed | | | −2.004 | 11.371 |
| Total Turns inside the Maze in degrees | Equal variances assumed | 9.892 | .003 | −2.436 | 36 |
| | Equal variances not assumed | | | −1.983 | 11.767 |

Figure 4.9: Independent samples T-Test.

# Chapter 5

# User Study II - The Environmental Impact on User Performance in Ubiquitous Immersive VR

> *"Observation is a passive science, experimentation is an active science."*
>
> — Claude Bernard

**Relevance to dissertation**

This chapter presents our second user study, conducted in 2014, investigating whether physical environmental conditions (i.e. being outdoors or indoors) impact users' spatial navigation ability in a ubiquitous immersive VR experience.

## 5.1 Background and motivation

Traditional VR deployments were conducted in controlled indoor laboratory settings. As VR continues to become more ubiquitous and is able to be deployed with less cumbersome hardware, the possibilities for deploying VR in a variety of environments increase. This introduces new practical and theoretical challenges to the VR community.

After our successful initiation with our Study I [see Chapter 4], we proceeded with our investigation into immersive spatial navigational performance to study the correlation between the physical and the virtual environment (indoors versus outdoors). We suspect that the environment, both physical and simulated, affects the overall spatial navigation performance involved in an immersive virtual experience.

## 5.2 Hardware and software design

A similar hardware/software setup like that in Study I was used for deploying Study II [See section 4.2]. The 3D virtual maze experience was developed using the Unity3D Professional game engine.

## 5.3 Study design

The study was designed to compare the effect of physical environments and their configuration on spatial navigation performance.

**Null hypothesis**: *There isn't a significant difference between shooting score in matched versus unmatched configuration of VE and the physical space.*

Figure 5.1: A user participating in our study of environmental impact towards spatial navigability in immersive VR.

**Alternate hypothesis**: *There is a significant difference between shooting score in matched versus unmatched configuration of VE and the physical space.*

Inspired by the results in Study I [see Chapter 4], we designed two similar immersive maze experiences with the structural difference of one of them being a simulated warehouse (indoor setting) and the other being a simulated urban environment (outdoor setting) [see Figure 5.1]. The study design is a 2x2 cross over study intended towards comparing the performance metric (i.e. speed and accuracy) between the following scenarios:

- User 'A' recruited inside a building (physically indoors) experiences the 'Inside Warehouse Shooting Virtual Experience'. This is a matched configuration between the physical and the virtual space where the user is physically partaking the VR experience while being indoors.
- The same User 'A' experiences the 'Outside Urban Shooting Virtual Experience' next. This is an unmatched configuration between the physical and the virtual space where the user is physically partaking the VR experience while being indoors.
- A different User 'B' recruited outside a building (physically outdoors) experiences the 'Outside Urban Shooting Virtual Experience'. This is a matched configuration between the physical and the virtual space where the user is physically partaking the VR experience while being outdoors.
- The same User 'B' experiences the 'Inside Warehouse Shooting Virtual Experience' next. This is an unmatched configuration between the physical and the virtual space where the user is physically partaking the VR experience while being outdoors.

### 5.3.1 Tasks

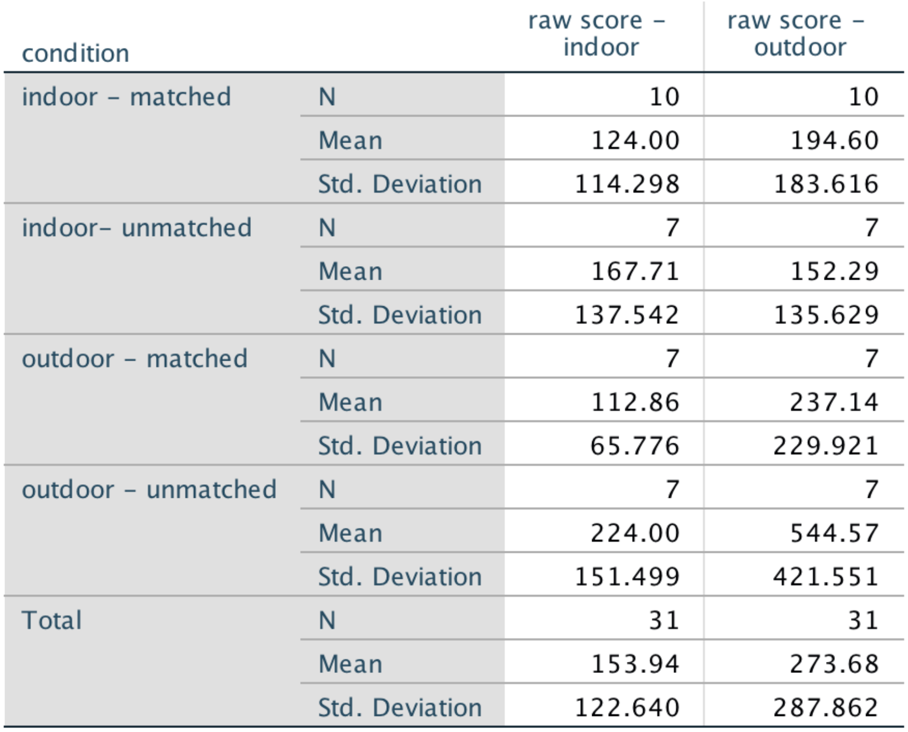
At the start of the virtual experience, the user puts on the UCAVE prototype [see Chapter 3], and they are inside a virtual maze. The recruitment protocol maintained alternating order assignment between the matched versus unmatched setting for the users. The user is first allowed a brief training session in which he/she is acquainted with the user input mechanics. Once complete, the user is given the task of shooting virtual targets in and around the VEs. The indoor setting and the outdoor setting are illustrated in Figure 5.2. The virtual task set is to shoot a total of 7 targets spread throughout the mazes. The scoring criteria is based on accuracy and distance from which the targets are hit. The users score higher if they hit the 'bulls-eye' target accurately from far. Based upon the deployment condition (i.e. matched or unmatched), once the user has completed the maze experience, they are given a break of 1 minute. After that, the system automatically starts the second maze experience. The users do not necessarily have to complete their first session successfully in order to start the second session.

Figure 5.2: A top down view of the Indoor Warehouse Environment and the Outdoor Urban Environment.

### 5.3.2 Measures

Data automatically recorded during the course of the maze navigation was used to measure the performance of each participant. For every session, we recorded, every 10 ms apart, the participant's spatial trajectory [see Figure 5.3] inside the maze along with orientation of gaze information. We also recorded raw unscaled scores for each participant. The data contained information retrieved and extracted from 31 participants with the following attributes: subject id, condition deployed (indoor versus outdoor; matched versus unmatched), raw score (indoor), raw score (outdoor), relative simulator sickness score (low: 16; high: 160), and presence score (low: -21, high: +21). We used SPSS to conduct the analysis of the data.

Figure 5.3: A top down view of the Indoor Warehouse Environment and the Outdoor Urban Environment with random users' trajectory mapped.



| condition | | raw score – indoor | raw score – outdoor |
|---|---|---|---|
| indoor – matched | N | 10 | 10 |
| | Mean | 124.00 | 194.60 |
| | Std. Deviation | 114.298 | 183.616 |
| indoor– unmatched | N | 7 | 7 |
| | Mean | 167.71 | 152.29 |
| | Std. Deviation | 137.542 | 135.629 |
| outdoor – matched | N | 7 | 7 |
| | Mean | 112.86 | 237.14 |
| | Std. Deviation | 65.776 | 229.921 |
| outdoor – unmatched | N | 7 | 7 |
| | Mean | 224.00 | 544.57 |
| | Std. Deviation | 151.499 | 421.551 |
| Total | N | 31 | 31 |
| | Mean | 153.94 | 273.68 |
| | Std. Deviation | 122.640 | 287.862 |

Figure 5.4: Descriptive statistics of shooting score by group (indoor versus outdoor; matched versus unmatched) in User Study II.

### 5.3.3 Population and Environment

We obtained approval from University of Georgia's institutional review board to conduct the user study at various high-traffic, indoor, public locations on our campus. We recruited people passing by our demonstration booth to try the experience and provide feedback to us on various usability topics. We gathered quantitative data on task performance, simulator sickness, and presence. We collected background demographic data on participants including age, gender, and ethnicity. For simulator sickness we used the Kennedy et al., Simulator Sickness Questionnaire [Kennedy et al., 1993] administered before and after the experience. For presence, we used the Steed, Usoh, Slater questionnaire from [Usoh et al., 2000]. Finally, we asked users for comments on the experience and system.

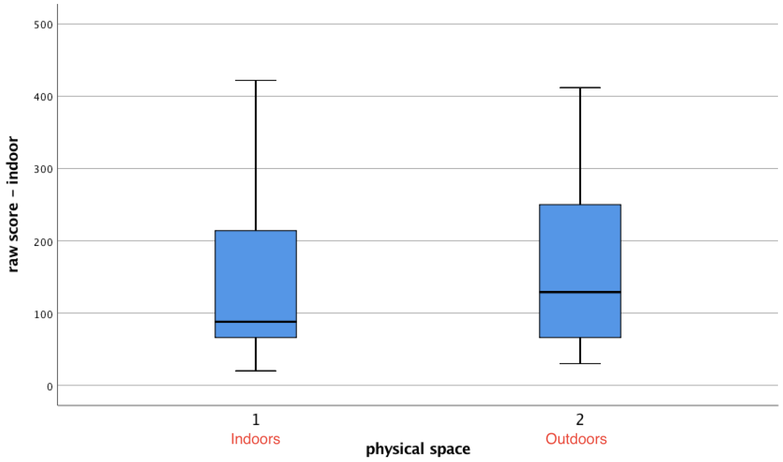


Figure 5.5: Boxplot showing raw score (indoor) inside the maze by group (indoor versus outdoor) in User Study II.

## 5.4 Results

We had 39 participants take the immersive experiences in total. 8 participants' data were discarded from the data analysis because their data logs became corrupted with garbage value during the study.

Within groups (indoor versus outdoor) descriptive statistics reveal that the mean raw shooting score inside the maze is lower (124) for condition indoor-matched first

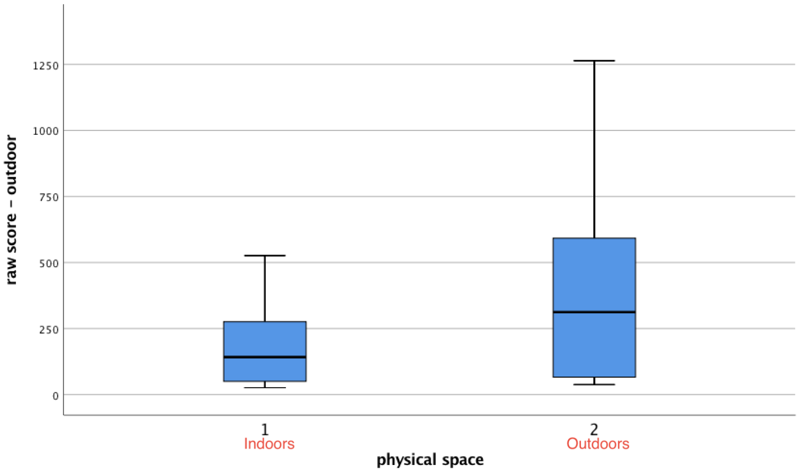


Figure 5.6: Boxplot showing raw score (outdoor) earned inside the maze by group (indoor versus outdoor) in User Study II.

than for condition indoor-unmatched second (168). A similar trend is observed between outdoor-matched first (237) and outdoor-unmatched second (545) [see Figure 5.4]. This is indicative of a trend, but we need inferential statistics to make an argument conclusively. We then proceeded with repeated measures analysis and found a significant impact (partial) on shooting score by matched versus unmatched configuration of VE and the physical space [see Figure 5.9]. The state of the VE (warehouse indoor versus urban outdoor) does significantly impact users' performance inside immersive VR [see Figure 5.11]. We found through an independent samples t-test that the first state of the VE whether matched or not with the actual physical space of deployment matters significantly for user performance if the state of VE is outdoor. We found that a matched outdoor setting (outdoor as physical space and outdoor as the VE) seems to be the best performing setting for our participants.

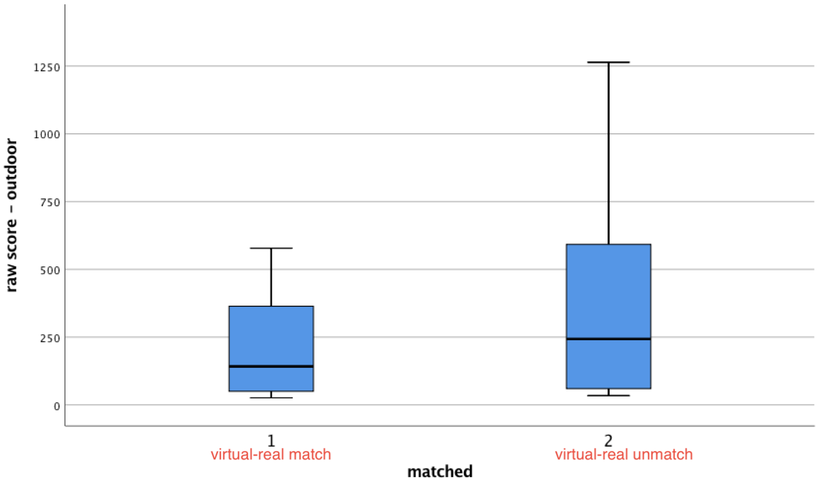


Figure 5.7: Boxplot showing raw score (indoor) inside the maze by group (matched versus unmatched) in User Study II.

## 5.5 Discussion

We *reject* our null hypothesis and accept the alternate hypothesis. Furthermore, we found that users are performing better (scoring high) when they aim using a precise eye-head-hand coordination in pointing at visual targets. This serves as a presence marker for users achieving high precision inside the VE. User performance in VR transfers between traditional, indoor deployments and outdoor deployments. As we continue to develop new, ubiquitous VR experiences and applications, these findings do alleviate environmental restrictions on the VR community.

**Additional findings**: Additionally, we found that users were tremendously exhausted after experiencing back-to-back immersive VR sessions. It is specifically worse if the par-

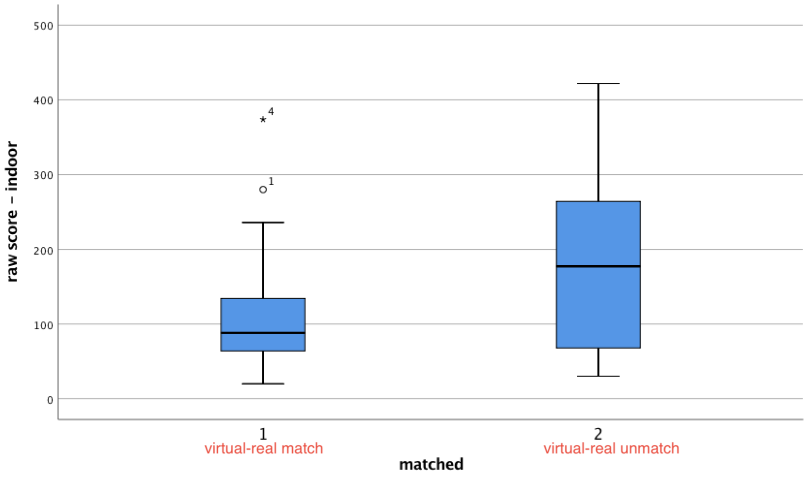
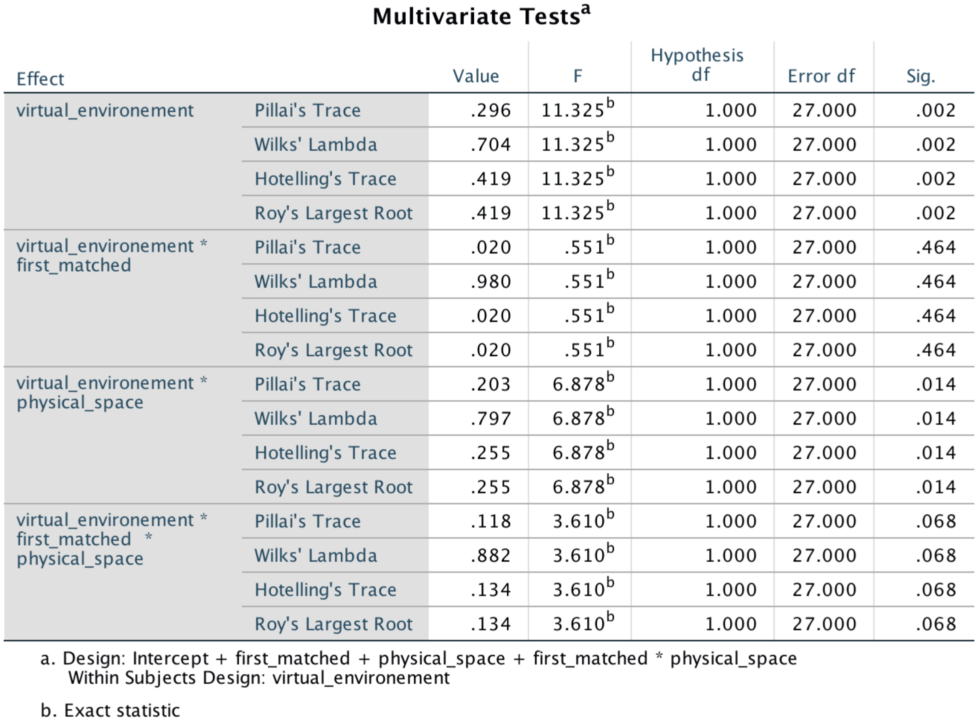


Figure 5.8: Boxplot showing raw score (outdoor) earned inside the maze by group (matched versus unmatched) in User Study II.

ticipant is outdoor during the day time. Anecdotally, many participants who experienced our immersive VR shooting experience outdoors were facing social awkwardness anxiety.

To summarize, in this study, we have described how to deploy and maintain immersive VR experiences anywhere (indoor and outdoor). We also measured the impact of being matched (physical to virtual) on user performance while using our ubiquitous VR system.

Having established the fact that being matched or not matched (physical space to VE) in immersive VR is partially important depending upon what state of VE you deploy first, the next step is to examine human factors and their impact on immersive VR user performance.



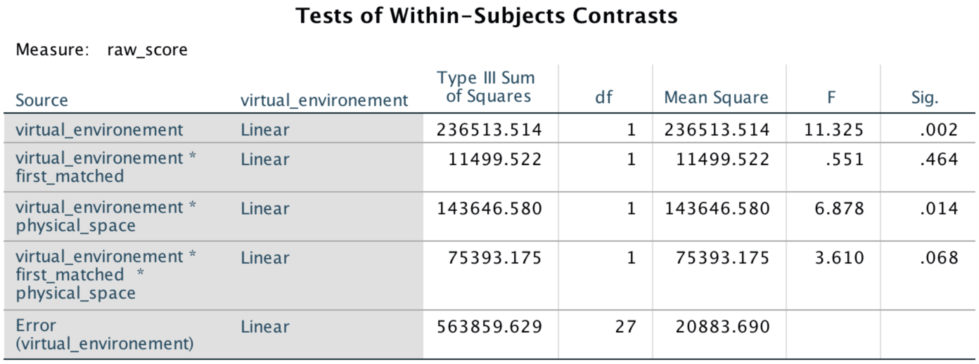
**Multivariate Tests**[a]

| Effect | | Value | F | Hypothesis df | Error df | Sig. |
|---|---|---|---|---|---|---|
| virtual_environement | Pillai's Trace | .296 | 11.325[b] | 1.000 | 27.000 | .002 |
| | Wilks' Lambda | .704 | 11.325[b] | 1.000 | 27.000 | .002 |
| | Hotelling's Trace | .419 | 11.325[b] | 1.000 | 27.000 | .002 |
| | Roy's Largest Root | .419 | 11.325[b] | 1.000 | 27.000 | .002 |
| virtual_environement * first_matched | Pillai's Trace | .020 | .551[b] | 1.000 | 27.000 | .464 |
| | Wilks' Lambda | .980 | .551[b] | 1.000 | 27.000 | .464 |
| | Hotelling's Trace | .020 | .551[b] | 1.000 | 27.000 | .464 |
| | Roy's Largest Root | .020 | .551[b] | 1.000 | 27.000 | .464 |
| virtual_environement * physical_space | Pillai's Trace | .203 | 6.878[b] | 1.000 | 27.000 | .014 |
| | Wilks' Lambda | .797 | 6.878[b] | 1.000 | 27.000 | .014 |
| | Hotelling's Trace | .255 | 6.878[b] | 1.000 | 27.000 | .014 |
| | Roy's Largest Root | .255 | 6.878[b] | 1.000 | 27.000 | .014 |
| virtual_environement * first_matched * physical_space | Pillai's Trace | .118 | 3.610[b] | 1.000 | 27.000 | .068 |
| | Wilks' Lambda | .882 | 3.610[b] | 1.000 | 27.000 | .068 |
| | Hotelling's Trace | .134 | 3.610[b] | 1.000 | 27.000 | .068 |
| | Roy's Largest Root | .134 | 3.610[b] | 1.000 | 27.000 | .068 |

a. Design: Intercept + first_matched + physical_space + first_matched * physical_space
Within Subjects Design: virtual_environement

b. Exact statistic

Figure 5.9: Repeated measures analysis for User Study IV; multivariate test.

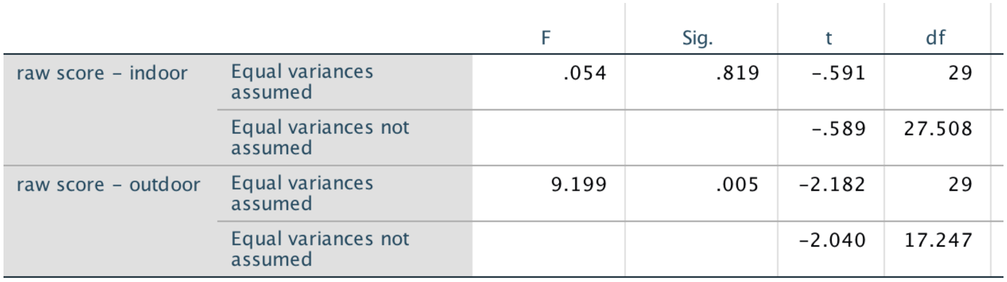


**Tests of Within-Subjects Contrasts**

Measure: raw_score

| Source | virtual_environement | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| virtual_environement | Linear | 236513.514 | 1 | 236513.514 | 11.325 | .002 |
| virtual_environement * first_matched | Linear | 11499.522 | 1 | 11499.522 | .551 | .464 |
| virtual_environement * physical_space | Linear | 143646.580 | 1 | 143646.580 | 6.878 | .014 |
| virtual_environement * first_matched * physical_space | Linear | 75393.175 | 1 | 75393.175 | 3.610 | .068 |
| Error (virtual_environement) | Linear | 563859.629 | 27 | 20883.690 | | |

Figure 5.10: Repeated measures analysis for User Study IV; test of within-subject contrast.



| | | F | Sig. | t | df |
|---|---|---|---|---|---|
| raw score - indoor | Equal variances assumed | .054 | .819 | -.591 | 29 |
| | Equal variances not assumed | | | -.589 | 27.508 |
| raw score - outdoor | Equal variances assumed | 9.199 | .005 | -2.182 | 29 |
| | Equal variances not assumed | | | -2.040 | 17.247 |

Figure 5.11: Independent samples T-Test.

# Chapter 6

# User Study III - The Human Factor Impact on User Performance in Ubiquitous Immersive VR

> *"Nothing has such power to broaden the mind as the ability to investigate systematically and truly all that comes under thy observation in life."*
>
> — Marcus Aurelius

**Relevance to dissertation**

This chapter presents our third user study, conducted in 2015-16, investigating whether self-reported physical fitness has any impact on users' spatial navigation ability in a ubiquitous immersive VR experience.

## 6.1 Background and motivation

Following our findings from the previous study [see Chapter 5], we regressed into a simplistic maze design as we found that users became terribly nauseated experiencing back-to-back immersive VR sessions. Because a goal of our research is to create more ubiquitous, user-friendly VR systems and experiences, we needed to mitigate the problem of users' nausea that we encountered in our prior study design. Nausea was at its worse when participants performed back-to-back tasks in immersive VR. For this experiment, we decided to design an experience using a single VR experience. Keeping the above points in mind, we designed a simplistic task set of finding a virtual dog avatar inside our third maze experience. We also diverted our attention to a more subjective (personalized) metric, namely the physical fitness, of users.

Physical fitness affects all parts of our lives, directly benefiting health and longevity, but also having effects on cognition and learning. While many have proposed using virtual reality as a means to improve or promote physical fitness (e.g. exergaming), the potential effects of physical fitness on cognition in virtual environments have yet to be explored. We take solving a maze in VR to be primarily a cognitive task, as the physical demands upon the user are minimal. Given the parallels found between real and virtual reality in so many domains, it would be reasonable to assume that at least some of the cognitive benefits would translate from the real world to the virtual world. With regards to physical activity, VR has been explored as a means to motivate individuals to exercise [Johnsen et al., 2014; Keum et al., 2015]. For example, Keum et al. sought to motivate overweight or obese individuals to exercise by using an exergame where the participant's avatar was generated using their body composition data. In this exergame, the participant used the generated avatar to navigate a virtual obstacle course by physically dodging, ducking, jumping, or running. Keum et al. found that their system could potentially achieve this goal although they had mixed reactions towards the avatar reflecting actual body composition data. Some participants were intrigued while others expressed negative opinions of seeing their physical appearance without modification.

While these studies explore a relation between physical activity and virtual reality, they do not address how physical activity can impact performance of a virtual task, such as navigating a 3D virtual maze. Research has been conducted comparing the use of real walking and other travel techniques in regards to performance of various tasks in virtual environments [Zanbaka et al., 2005; Suma et al., 2010a]. Generally, it has been found that real walking results in improved performance compared to virtual travel techniques, such as using a joystick, especially in regards to higher mental processes [Zanbaka et al., 2005; LaViola Jr et al., 2017]. However, Suma et al. found that there was not a significant difference between real walking and a gaze directed technique regarding navigation performance and recall of environment details of a complex virtual environment. However, this still does not ask the same question being pursued here as it is looking at physical activity in terms of the interaction technique and not a characteristic of the user affecting their performance. In this study, we investigated how a user's physical activity profile impacts their virtual task performance as related research indicates that there is a positive correlation between physical fitness and higher levels of cognition [Hillman et al., 2008]. Another characteristic of the users that can impact virtual task performance is gaming experience. Individuals with gaming experience are more likely to be familiar with the interface we used for the study and thus are more likely to outperform non-gamers [Smith and Du'Mont, 2009]. Smith et al. asked participants to find the exit to a maze as fast as possible and found that participants with higher perceived level of skill regarding video games correlated to faster completion times. This means that individuals who perceived themselves as being more proficient at video games completed the maze faster than those who did not. As a result, we also asked our participants to report the number of hours they spent per week playing video games.

Our basic premise with this research is that physical fitness, being a highly impactful variable in our lives, may be similarly impactful in our virtual world. Beyond the known cognitive benefits of fitness [Hillman et al., 2008], there are numerous ways that physical fitness may play a role in virtual reality. For example, physical fitness may have a high (likely inverse) correlation to watching television and/or playing video games. Or, physical fitness may indicate a stronger preference for moving, or perhaps increased navigation capability. Perhaps people who move more in the real world are less susceptible to motion or simulator sickness. We also considered that people who are more physically fit might have more well tuned perceptual systems, or might have a stronger 'link' to the physical world, which is a reason to suppose that physical fitness could reduce performance. In this chapter, we describe our virtual maze application as well as the detailed mobile 3DUI system design. We also report the encouraging results of a user study of 90+ users enrolled at the university physical activity center.

Figure 6.1: A user trying out our Study III 3D maze experience outdoors.

## 6.2 Hardware and software design

Keeping in mind the simplicity of the task and logistics of running the study outdoors we opted for a ubiquitous VR system which only included a HMD and a controller. Figure 6.1 shows a user trying out our maze experience in full gear. We opted for Samsung Galaxy Gear VR as our HMD and Samsung Galaxy Note 4 as our primary display. For user controls in the maze, we opted for a Bluetooth compatible Madcatz C.T.R.L. gamepad controller which connects easily with the Samsung Galaxy Note 4.

The 3D virtual maze experience was developed using the Unity3D Professional game engine. While each user is busy solving the maze, the system software keeps an active log of user trajectory data along with their head orientation data. Furthermore, the system software also logs relevant event data such as user quitting the maze experience unsuccessfully or user finding the target inside the maze successfully.

## 6.3 Study design

The study was designed to investigate the effect of physical fitness as a criterion towards spatial navigation performance.

**Null hypothesis**: *There is a positive correlation between self-reported physical fitness score and maze completion time.*

**Alternate hypothesis**: *There is a negative correlation between self-reported physical fitness score and maze completion time.*

From our results in Study II [see Chapter 5], we regressed our level design and the corresponding task model to a simplified maze navigation with only one target as objective.

### 6.3.1 Tasks

The VR experience was designed around the idea of a quick in-and-out experience with the affordances of the wearable VR system described in section 6.2 that lets users try out the experience in the shortest span of time in a familiar outdoor environment. This was pivotal in recruiting and managing a large set of VR users. We used a commercially available ubiquitous VR system.

The focal point of the immersive experience is to traverse a 3D maze environment and find a specified target in a minimum amount of time. To add to the experience, we used a university mascot as the intended target inside the maze. Participants were equipped with a HMD and gamepad and given the instruction to find the university mascot within a virtual maze. Once the user finds the target, they see the animated university mascot with a welcome message. Since our primary pool of participants were university students, faculty and staff, the problem of a maze navigation became unique and interesting to the local taste. The target audience were adults of age 18 and older.

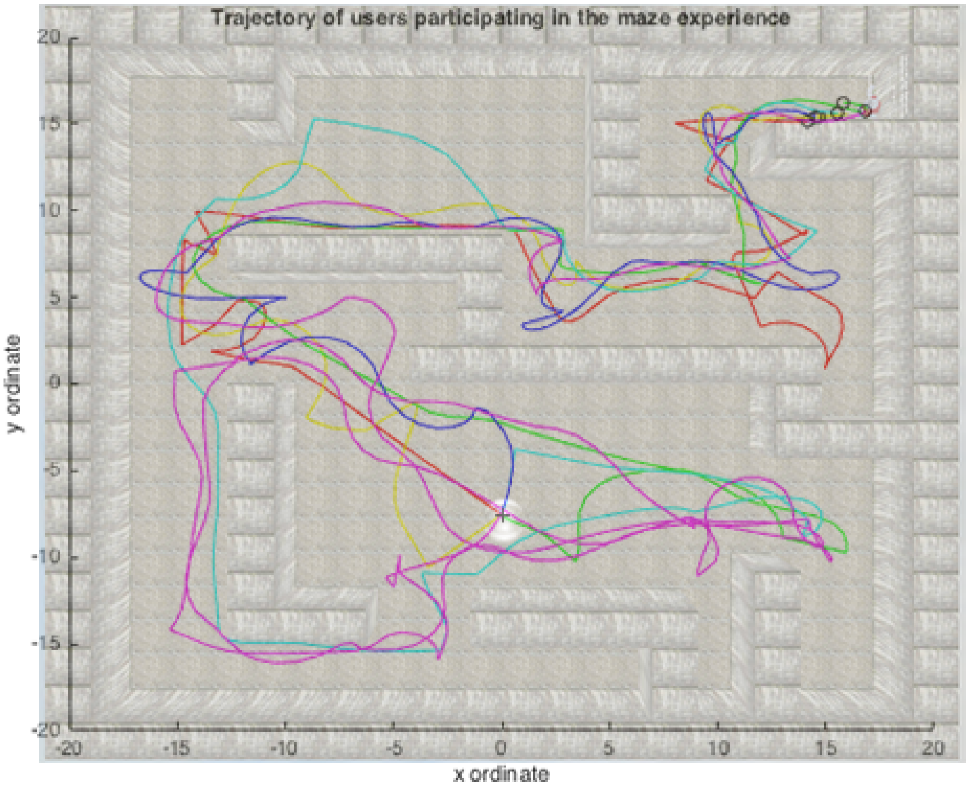


Figure 6.2: Trajectory map of six random users completing the maze.

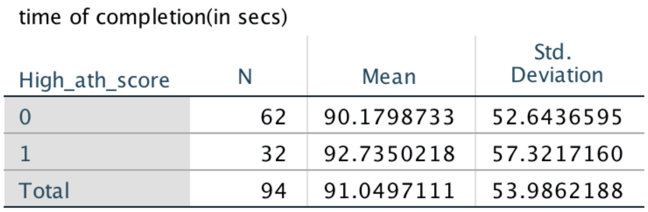
### 6.3.2 Measures

The measures for the study primarily consisted of data recorded from the demographic forms filled by the users and the trajectory data automatically logged during the course of the immersive experience. This consisted of the absolute position and gaze direction of players, events logged at critical juncture of the game, and their respective time of completion [see Figure 6.2]. In addition, the users also filled out a pre-simulator and a post-simulator sickness questionnaire [Kennedy et al., 1993] and a presence questionnaire [Usoh et al., 2000] related to the immersive experience. We used Matlab and SPSS to conduct the analysis of the data.

### 6.3.3 Population and Environment

99 physically motivated subjects with a mean age of 22.82 years (SD=5.904) participated in our 3D maze experience over a course of 4-month period during the Fall semester of 2015. We recruited these participants at a local physical activity and recreation center. In compliance with the University of Georgia's institutional review board guidelines, every participants' consent was obtained and recorded on paper forms. Furthermore, the users were asked to fill out a series of forms including a general demographic questionnaire, pre-simulator and post-simulator sickness questionnaire and a presence questionnaire. The data contained the following attributes: subject id, date, athletic score, gender, age, 20/20 vision, fitbit, event type, time of completion, relative simulator sickness score (Low: 16; High: 160), presence score (Low:-21, High:+21).

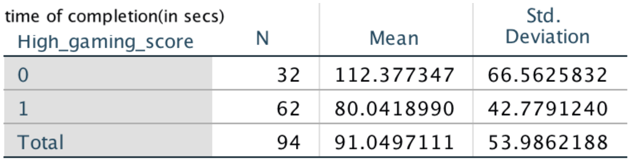
Our experiment was conducted in an outdoor setting during daytime in between noon and 5 in the evening. The physical location was intentionally chosen to be at the entrance of the local physical activity center where there is a higher chance of recruiting physically motivated subjects.



time of completion(in secs)

| High_ath_score | N | Mean | Std. Deviation |
|---|---|---|---|
| 0 | 62 | 90.1798733 | 52.6436595 |
| 1 | 32 | 92.7350218 | 57.3217160 |
| Total | 94 | 91.0497111 | 53.9862188 |

Figure 6.3: Descriptive statistics of time of completion of maze by group (high versus low athletic score; binned) in User Study III.



time of completion(in secs)

| High_gaming_score | N | Mean | Std. Deviation |
|---|---|---|---|
| 0 | 32 | 112.377347 | 66.5625832 |
| 1 | 62 | 80.0418990 | 42.7791240 |
| Total | 94 | 91.0497111 | 53.9862188 |

Figure 6.4: Descriptive statistics of time of completion of maze by group (high versus low gaming score; binned) in User Study III.

## 6.4 Results

Out of 99 recruited subjects, 6 participants' data have missing information regarding their respective gender.

Within groups (athletic score) descriptive statistics reveals that the group of participants who reported higher athletic scores took slightly more time on average to solve the

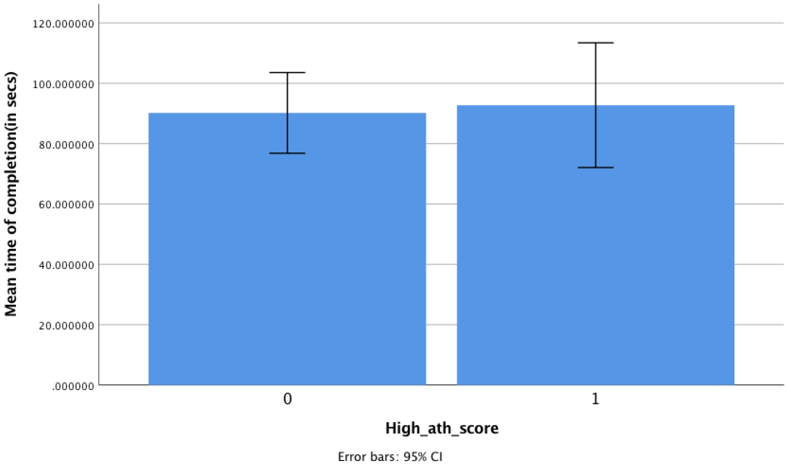


Figure 6.5: Boxplot showing time of completion of the maze by group (high athletic score reported; binned) in User Study III.

maze than the group who reported lower athletic score [see Figure 6.3]. However, participants who reported higher gaming hours score tend to solve the maze much more quickly (32.33 secs on average) [see Figure 6.4 and Figure 6.6]. Similarly, Figure 6.8 shows that the group of participants who reported very low gaming score of zero, that is the non-gamer group, took more time on average to complete the maze than the rest of the participants who reported high gaming score, that is the gamer group. This is indicative of a trend, but we need inferential statistics to make an argument conclusively. Furthermore, Figure 6.9 shows a positive correlation scatterplot between the time of completion of the maze (in seconds) and the age of the participants. We also found that female participants in our study spent higher time completing the maze on average than the male participants in our study [see Figure 6.7]. These findings combined suggests that age, gaming pro-

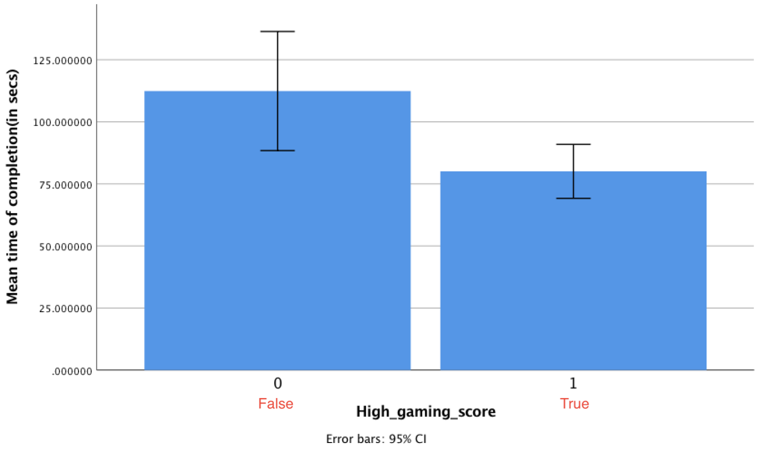


Figure 6.6: Boxplot showing time of completion of the maze by group (high gaming hours score; binned) in User Study III.

file, and gender of immersive VR users play a pivotal role in predicting their success in completing immersive VR tasks, specifically navigational tasks.

Next, we proceed to generate correlation matrix from the dataset. Pearson correlation was used to measure the degree of association between attributes. A visual summary of the Pearson correlation matrix is shown in Figure 6.10.

Some attributes, such as age, showed a correlation with time, but this could be related to the population of the study, which consisted of college students that were polled outside of athletic facilities on a college campus, and had a standard deviation (SD) of 5.90 years. Athletic score is not found to be significantly correlated to the dependent variable (time of completion of the maze).

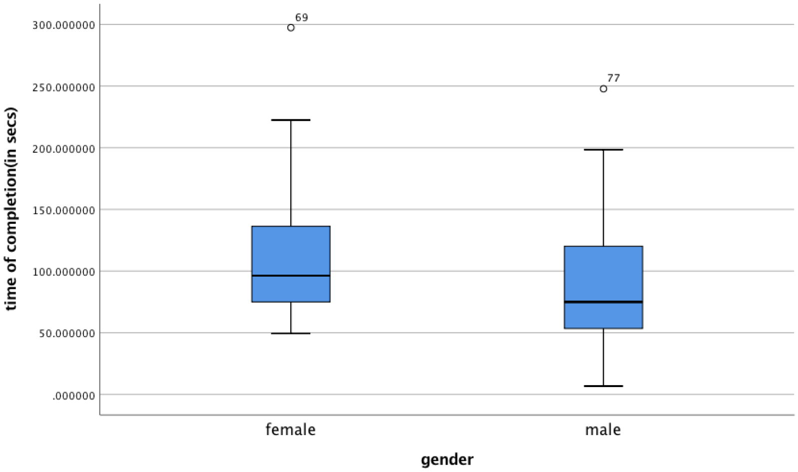


Figure 6.7: Boxplot showing time of completion of the maze by group (gender) in User Study III.

## 6.5 Discussion

We fail to *reject* our null hypothesis. However, we found that the gaming profile of immersive VR users is a metric that seems to affect immersive VR performance significantly and needs to be further evaluated as a predictor of success for immersive VR performance. We think gender and gaming profile is intertwined culturally as we see a lot more young male gamers in our study than female gamers among our participants. We speculate gaming profile and familiarity to gaming apparatus such as gamepad controllers affect user performance in immersive VR.

**Additional findings**: During the initial phases of the user study, we had concerns regarding infrastructure and deployment. Furthermore, we faced design challenges in

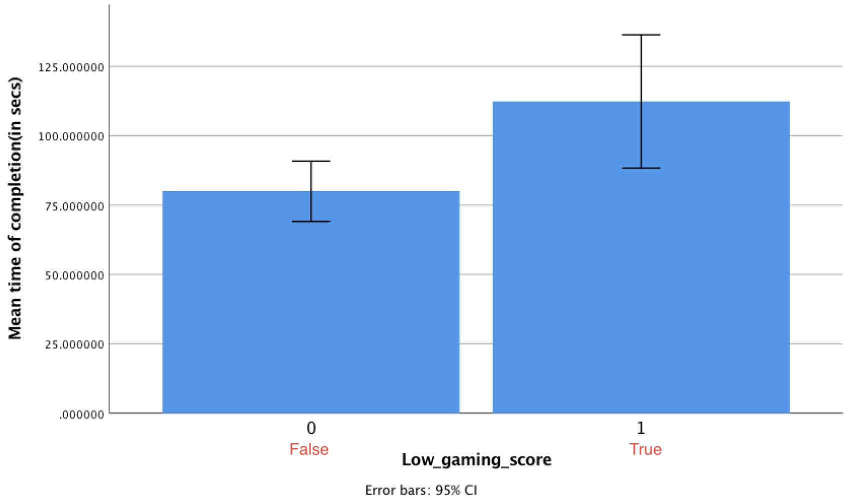


Figure 6.8: Bar graph with error bars showing mean time of completion of the maze by group (Low gaming hours score; binned) in User Study III.

conducting the study outdoors such as choice of location, ease of use, hand-off between users and recruitment in general. We were able to address all of these methodically during the course of the study.

To summarize, in this study, we have measured the impact of self-reported fitness assessment (athletic score) on user performance while using a ubiquitous VR system.

Having established the fact that athletic score has no bearing on immersive VR user performance, the next step is to examine technical factors, such as immersion, and their impact on immersive VR user performance.

* * *

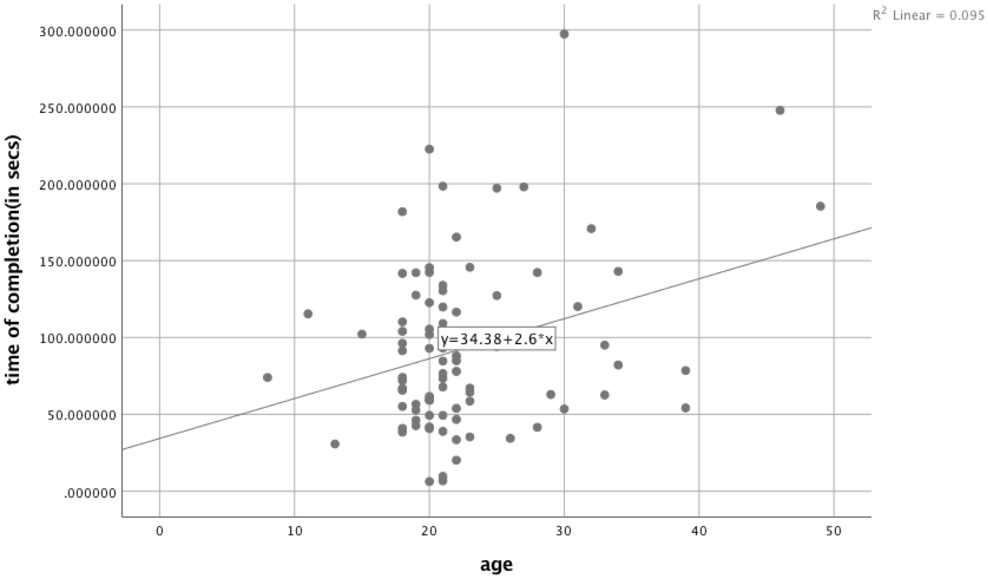
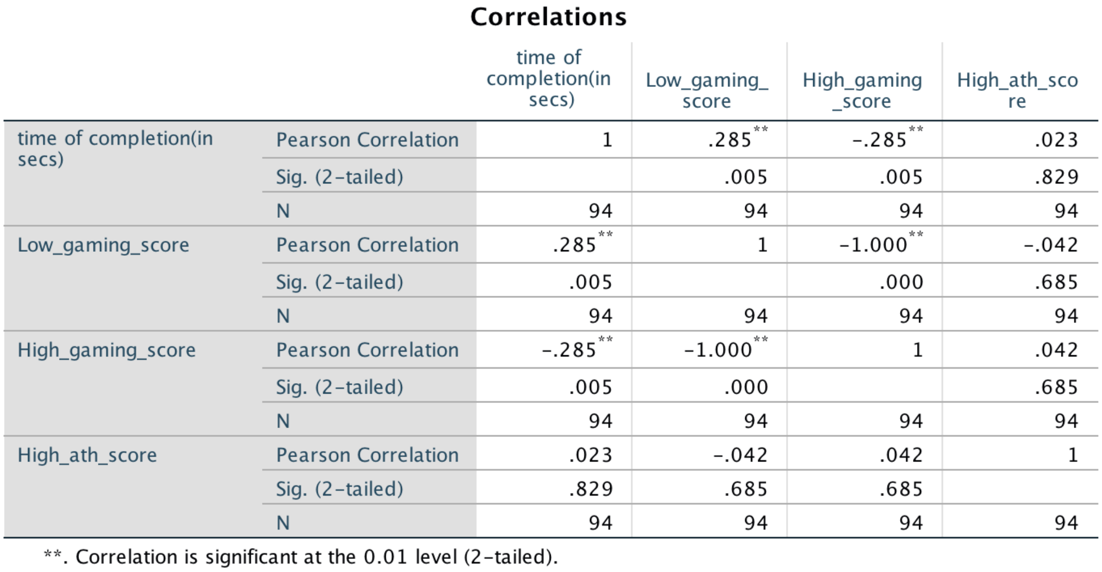


Figure 6.9: Graph showing scatterplot of time of completion of the maze as the y-axis and age of the participants as the x-axis in User Study III.



**Correlations**

| | | time of completion(in secs) | Low_gaming_score | High_gaming_score | High_ath_score |
|---|---|---|---|---|---|
| time of completion(in secs) | Pearson Correlation | 1 | .285** | -.285** | .023 |
| | Sig. (2-tailed) | | .005 | .005 | .829 |
| | N | 94 | 94 | 94 | 94 |
| Low_gaming_score | Pearson Correlation | .285** | 1 | -1.000** | -.042 |
| | Sig. (2-tailed) | .005 | | .000 | .685 |
| | N | 94 | 94 | 94 | 94 |
| High_gaming_score | Pearson Correlation | -.285** | -1.000** | 1 | .042 |
| | Sig. (2-tailed) | .005 | .000 | | .685 |
| | N | 94 | 94 | 94 | 94 |
| High_ath_score | Pearson Correlation | .023 | -.042 | .042 | 1 |
| | Sig. (2-tailed) | .829 | .685 | .685 | |
| | N | 94 | 94 | 94 | 94 |

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 6.10: Correlation matrix.

# Chapter 7

# User Study IV - The Technical Factor Impact on User Performance in Ubiquitous Immersive VR

> *"Science is built up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house."*
>
> — Henri Poincaré, Science and Hypothesis, 1905

This work has been published as a preprint on ArXiv (https://arxiv.org/abs/1805.09454).

**Relevance to dissertation**

This chapter presents our fourth user study, conducted in 2016-17, evaluating the significance of immersive versus non-immersive user interfaces and their impact on immersive VR user performance. We investigate individual factors such as, prior exposure to video-gaming, age, and gender, and evaluate if they have any impact on user performance when it comes to spatial maze navigation in immersive VR.

The study design has leveraged our UCAVE framework [see Chapter 3] to deploy a virtual maze that is similar in context to Study III [see Chapter 6]. It should be noted that the VR hardware setup for this study design has been minimalized (similar to Study III) to using only a smartphone-based HMD and a wireless controller. With the mobile hardware configuration introduced earlier [see Chapter 3], we were able to showcase the feasibility of the democratization of VR technology using commodity hardware. Other researchers have followed our design philosophy [Thomas et al., 2014a; Steed and Julier, 2013] to build their own mobile VR systems. A major trend of the successful commercialization of HMD technology in the industry followed suit with products such as Oculus Rift, Samsung Gear VR, and HTC Vive.

With this chapter, we refocus the attention of our research from building a standardized VR system to evaluating what immersive VR brings to users in terms of adding performance value.

## 7.1 Background and motivation

Spatial navigation is one of the core abilities of human beings. It is a useful skill set that we employ on a daily basis to navigate building interiors or busy streets to reach our destinations. The act of navigating a physical environment requires the simultaneous operation of both cognitive and motor functions [Spiers and Maguire, 2006]. The majority of VR experiments are designed with spatial navigation in mind as the primary means for exploring VEs [Werkhoven et al., 2014]. That said, the potential implications of VE interface and VR task model design on individual user performance in VR have yet to be explored adequately. As a result, understanding the underlying concepts of spatial navigation as a mathematical construct and its relationship to immersive VR user performance is particularly important, especially if we were to adopt VR exercises designed to promote navigation skill set building in users with measurable gain in output.

In this work, we presume that the prior video-gaming experience, age and the gender of the users participating in a VR study impacts their respective performance in executing immersive VR tasks. This study has been extended from earlier work examining how physiological factors affect user performance in immersive VR [see Chapter 6]. In this chapter, we describe our virtual maze application as well as the detailed system design. We report an extended analysis conducted on the recorded user trajectory data. To that end, we defined a set of mathematically derived features generalized for each trajectory such as distance traveled, decision points reached inside the maze, positional curvature, head rotation amount, and coverage of the maze.

## 7.2 Spatial navigation research in immersive VR

Our application and system is built upon the strategies, technology, and research involved in previous studies conducted on the topic of spatial navigation in immersive VR. A number of researchers have addressed issues related to spatial navigation and travel metaphors in immersive VEs over the years [Bowman et al., 1998b; Suma et al., 2010b,a; Zanbaka et al., 2005; Jeong et al., 2005]. A subset of these works have also looked into the affects of prior video gaming experience on immersive VR navigation performance

Figure 7.1: UCAVE Study IV - Immersive (top) and non-immersive (bottom) perspectives of all study participants at the start of the maze experience.

[Smith and Du'Mont, 2009].

In 1998, Bowman et al. proposed a formalized methodology and framework [Bowman et al., 1998b] for the evaluation of travel techniques in immersive VEs. The basic construct of their framework was a taxonomy of travel techniques. Their experimental analysis revealed the need to gather more information about user analytics inside VEs. In a second study, Bowman et al. studied the effects of various travel techniques on the spatial orientation [Bowman et al., 1999] of users inside immersive VR environments. At the same time, Ruddle et al. introduced a formal study comparing HMDs and desktop displays [Ruddle et al., 1999]. The objective of this study was to perform a baseline investigation that compared the two different types of displays. They found that participants using the HMD navigated the virtual buildings significantly more quickly, and developed a significantly accurate sense of relative straight-line distance. Behavioral analyses showed that participants took advantage of the natural, head-tracked interface provided by the HMD in ways that include "looking around" more often while traveling through the VE and spending less time being stationary while choosing a direction in which to travel.

In 2009, Smith et al. conducted a research study to look into the impact of previous computer gaming experience, user perceived gaming ability, and actual gaming performance on navigation tasks in a VE [Smith and Du'Mont, 2009]. They found that perceived gaming skill and progress in a linear first person shooter (FPS) game were found to be the most consistent metrics. Both perceived gaming skill and progress in a linear FPS game bore a relationship to performance in trivial searches, primed searches, the number of mistakes when performing an advanced travel technique (jumping) and in traveling time requiring high speed and accuracy. Smith et al. [Smith and Du'Mont, 2009], stated 'this may require the development of a gamer profile including both similar metrics to those used in this paper, metrics over other 3D interface tasks such as selection and manipulation and metrics for subjective conditions such as user disorientation, cybersickness and presence.' In 2010, Suma et al. reported a user study comparing real walking with three virtual travel techniques; namely, gaze-directed, pointing-directed, and torso-directed travel [Suma et al., 2010b]. Suma et al. found that real walking is superior in terms of user performance as it allowed more cognitive capacity for processing and encoding stimuli than pointing-directed travel metaphors. They also found that male participants were slower and performed significantly worse on the attention task when the spatial task became more difficult in contrast to female participants. In another related study, Suma et al. reported that for complex VEs with numerous turns, virtual travel techniques are acceptable substitutes for real walking if the goal of the application involves learning or reasoning based on information presented in the environment [Suma et al., 2010a].

Another component of studying spatial navigation is spatial trajectory analysis. In 2005, Zanbaka et al. described a between-subjects experiment that compared four different methods of travel, their effect on cognition, and paths taken in an immersive VE [Zanbaka et al., 2005]. This study used participants' trajectory (position and head orientation) data in post-analysis by creating overlays that ultimately revealed further differences in travel techniques. This study favored a large tracked space over other travel techniques in VR for applications where problem solving and interpretation of material is important or where opportunity to train is minimal. Jeong et al. in 2005, reported on the differentiation of information-gathering ability in the real and the VE [Jeong et al., 2005]. An important finding of their study was that the users path of finding information was similar, their information gathering ability differs between the real and the VE.

This chapter does not address the cognitive issues related to spatial exploration on an individual basis. Rather our approach distinguishes task performance (as a trend) between two categories of users (gamers and non-gamers) using VR systems. More than one performance metric for solving a maze in VR has been deployed, which allowed for a nuanced discussion of navigation abilities.

Figure 7.2: UCAVE Study IV - Key locations and decision nodes of the maze.

Prior work on the evaluation of ubiquitous, smartphone driven 3DUIs helped guide our system architecture [Basu et al., 2012b, 2013]. A light-weight VR system is logistically a sound design when it comes to recruiting higher number of subjects for a research study. Other studies exist that looked into physical activity as a potential marker for performances in immersive VR environments. One such study suggested that physical activities of users can be a predictor for VR task performance [Basu et al., 2012b]. In regards to physical activity, virtual reality has also been explored as a means to motivate individuals to exercise, a concept better known as VR exergaming [Johnsen et al., 2014]. While all these studies explore the relationship between physical activity and VR performance, there has been a lack of concrete connections between them. In contrast to quantifying physical fitness of users as suggested by Basu et al.[Basu et al., 2016; Johnsen et al., 2014], our approach shifts the attention of the user performance predictor to the gaming profile.

## 7.3 Application

Our maze application requires the user to navigate a maze and find multiple target sites. For consistency, every player had a fixed starting point and fixed targets to reach in the maze. The context of the maze experience was similar to Study III [see Chapter 6], in which the subject is required to find and rescue another human (avatar). The task included finding a clue (minimap) before finding the human avatar and then tracing back the path to the entrance of the maze. On average, the participants spent *4.64* minutes in the immersive user interface setting and *6.18* minutes in the non-immersive user interface setting.

### 7.3.1 Game Design

The focal point of our VR experience was to traverse a maze environment, find multiple target sites and trace back your path. To add to the experience, we used an altruistic framework by setting up a background story of a lost traveler inside the maze. Each participant was given the tasks of searching for and rescuing the lost character in the maze. To better emphasize this point, a restriction was placed upon the participant in the form of finding a map of the maze first. Once the user was successful in finding the map location, the user was then asked to find the lost character in the maze. Upon meeting the character, which is an animated humanoid avatar, the participants were required to trace back their path to the entrance of the maze to complete the experience. The maze design also included strategically placed unique props (box, first-aid kit, etc.) to help with user localization and memory. Various key locations, including targets and props in our maze design, are illustrated in Figure 7.2.

### 7.3.2 System Hardware

Our system setup included a mobile HMD and a wireless gaming controller. We opted for Samsung Galaxy Gear VR as our HMD solution and Samsung Galaxy S6 Edge+ with 5.7 inch screen size at 2560 pixels x 1440 pixels (518 ppi) screen resolution as our primary smart phone display. For user controls in the maze, we opted for a Bluetooth compatible *Madcatz C.T.R.L.* gamepad controller which connects easily with our display. A typical system setup deployed for the study is illustrated in Figure 7.3.

Figure 7.3: UCAVE Study IV - A randomly selected participant taking the maze experience.

### 7.3.3 System Software

The VR maze experience was developed using the Unity game engine and deployed on the HMD device as an Android app. While each participant was busy solving the maze, the system software kept an active log of their in-session trajectory data along with their head orientation data every 10 milliseconds. Furthermore, the system software also logged relevant event data such as participants quitting the maze experience or participants finding the targets successfully. A visual example of participant tracking algorithm is illustrated in Figure 7.4.

Once the user data was collected, scripts developed in C# programming language were used to analyze the users' trajectory data in Unity game engine. These scripts parse through user transformation (x,y,z) in real-time and visualize their search patterns in the maze. This, in turn, allows to confirm visually emerging differences in user performance in immersive VR. This sort of visual analysis can be generalized to apply to other studies concerning spatial navigation in immersive VR.

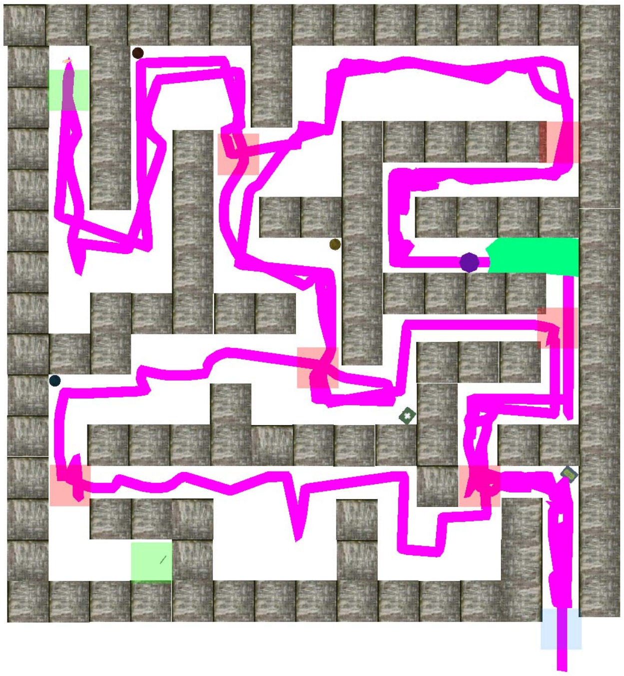
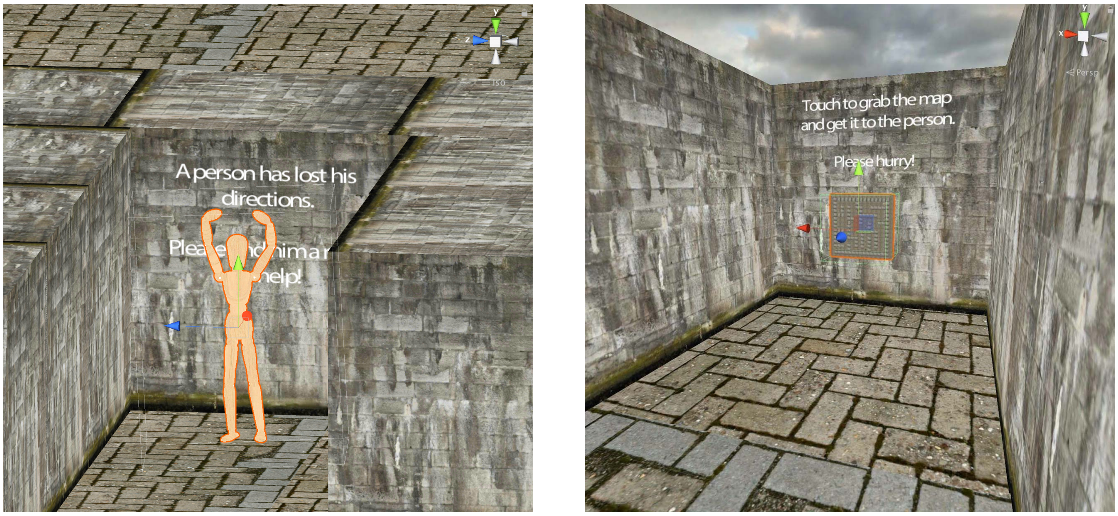


Figure 7.4: UCAVE Study IV - Visualization of a randomly selected participant's spatial trajectory data including gaze information represented as highlighted in cyan.

## 7.4 Study design

**Null hypothesis**: *There isn't a significant impact on users' ability to successfully navigate a 3D maze under the influence of technical factors such as immersive, non-immersive user interface.*



(a) 3D mannequin model
(b) 3D minimap model

Figure 7.5: UCAVE Study IV - Targets inside the maze.

**Alternate hypothesis**: *There is a significant impact on users' ability to successfully navigate a 3D maze under the influence of technical factors such as immersive, non-immersive user interface.*

The primary goal behind the maze experience is to understand how users with varying degree of exposure to video gaming solve a complex three dimensional immersive navigation problem. We wanted to quantify spatial decision making in terms of user activity in the maze. To this end, we conducted a 2 x 1 study with user type being one of our independent variables. We recorded spatial user activity, including gaze activity, every 10 millisecond apart to help develop a model for spatial navigation performance. The experiment required users to navigate a maze with a three-fold task model. The following subsections describe the study design in details.

### 7.4.1 Population and Environment

Over a course of 8 months, 40 self-motivated participants (mean-age = 35.93; SD = 11.11) volunteered for our study. Table 7.1 shows the breakdown of the two study groups by population demographics. These participants comprise a mix (by age, profession, background) of university staff and students at Emory University's main campus. In compliance with the Institutional Review Board guidelines of both University of Georgia and Emory University, every participant's consent was obtained and recorded on paper forms. Furthermore, the users were asked to fill out a series of forms including a general demographic questionnaire, pre-simulator and post-simulator sickness questionnaire and a presence questionnaire. Additionally, these users were also asked to fill out a self-reported gaming profile assessment form. Each user was then tasked to solve the same maze problem twice using an immersive user interface and then a non-immersive user interface. The order of deployment for each user was random and can be classified between the following two categories:

**Condition 1.** Immersive first, and then non-immersive

**Condition 2.** Non-immersive first, and then immersive

Each participant was recruited using an online recruitment drive advertised through the internal university mailing list. A specific laboratory was chosen to run the sessions with only one participant at a time. The choice of our study space was particularly critical to remove any additional social anxiety within our participants. Our study investigator sat down with our participants and would start conversing to ease them into our study.

Table 7.1: UCAVE Study IV - Study demographics based on the questionnaires. 'Player Level' is a derived scale reflecting participant's involvement and approach to video-gaming. 'Gamer' versus 'Non-Gamer' reflects the self-assessment of a user being a video-gamer.

| | | Gamer | N-Gamer |
|---|---|---|---|
| Participants | | 21 | 19 |
| Gender | Male | 14 | 4 |
| | Female | 7 | 15 |
| Player Level | Novice | 0 | 12 |
| | Casual | 6 | 6 |
| | Pro | 12 | 0 |
| | Hardcore | 2 | 0 |
| | Experiential | 1 | 1 |

Upon agreeing to our study requirements, a participant would start his/her first round of maze solving followed by a five minute break before starting his/her second round. The order of deployment for each user was random. The study investigator made sure to capture an equal number of participants for each category of deployment. Between the two sessions, the users were given five minute of break time to normalize their fatigue level before starting their next session.

### 7.4.2 Measures

Data automatically recorded during the course of the maze navigation was used to measure the performance of each participant. For each session, we recorded, every 10 millisecond, the participant's spatial trajectory inside the maze along with orientation of gaze information (Figure 7.4). This allowed us to effectively playback and calculate each participant's spatio-temporal activity including, but not limited to, time spent at decision nodes in the maze and cumulative gaze rotation at decision nodes in the maze.

In addition, the participants filled out background survey questionnaires with emphasis on video gaming activity profiling, pre-simulator and post-simulator sickness questionnaire (SSQ) [Kennedy et al., 1993] and a presence questionnaire [Usoh et al., 2000]related to their immersive maze experience.

The data contained information retrieved from 40 participants with the following attributes: subject id, date, player profile, gender, age, 20/20 vision, gaming hours, athletic score, condition of deployment, time of completion, relative simulator sickness score (low: 16; high: 160), and presence score (low: -21, high: +21). Furthermore, we introduced a derived scale of attribute based on participant's self reported gaming hours per week and their video-gaming exposure profiling which we have termed as 'Player Level' [see Table 7.1]. Additionally, for deep exploration of the trajectory data, we defined a set of mathematically derived features generalized for each trajectory such as distance traveled, decision points (nodes) reached inside the maze, positional curvature, head rotation amount, and coverage of the maze. Some of these trajectory features are illustrated in Figure 7.6. Positional curvature feature refers to the curvature of the trajectory calculated per frame between successive position vectors. Rotation amount feature refers to the unsigned angle calculated per frame between successive head rotation transforms stored as Quaternions. Coverage feature is simply the number of unit cubes covered (area) by the user, calculated per frame. We used R and SPSS together to conduct the analysis of the trajectory data.

Table 7.2: UCAVE Study IV - Features extracted from users' trajectory data for deep exploration and their corresponding definitions.

| Features | Definition |
|---|---|
| Distance traveled | It is the total length of the path traveled between two positions. |
| Coverage | Total number of unit cubes covered (area). |
| Number of decision points reached | Total number of decision points covered in the maze. |
| Positional Curvature | The signed angle of curvature between two consecutive position vectors. |
| Head rotation amount | The unsigned head rotation angle between two consecutive rotation transforms. |

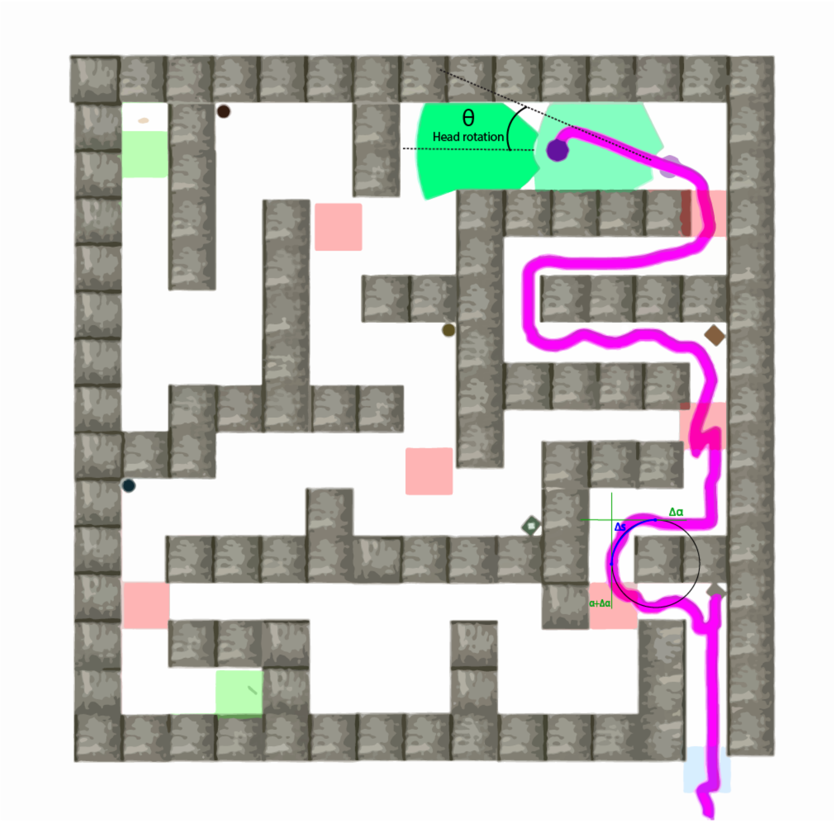


Figure 7.6: UCAVE Study IV - Visualization of two trajectory features: positional curvature and head rotation amount.

We obtained information from each sessions (immersive and non-immersive user interface). Pre-experience and post-experience survey questions relevant to this analysis are shown in Table A.1.

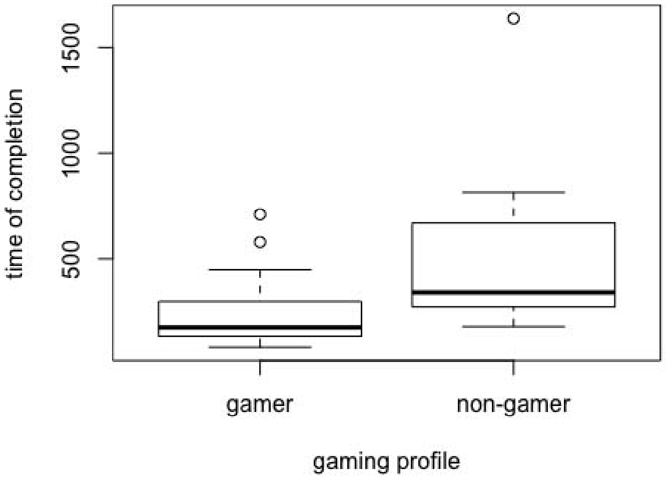


Figure 7.7: UCAVE Study IV - Time of completion is significantly less for participants who self-reported their gaming profile (gprofile) as gamers.

### 7.4.3 Procedure and Tasks

At the start of the experiment, participants were given elaborate verbal instructions explaining the experimental procedure. Both the gamer and the non-gamer group were then interviewed in order to profile their background and account for prior exposure to video gaming. The participants were given an overview of the technology involved and were explained how to wear a HMD and control their in-game avatar using the controller. They were also explained their responsibility towards the study (finding the targets inside the maze in a specific order, and if they were feeling nauseated, then they should immediately stop their VR experience). The participants were explicitly told that there were no time limits to their sessions and were advised to take their time to solve the maze. The participants would then initiate their two session maze experience with ei-

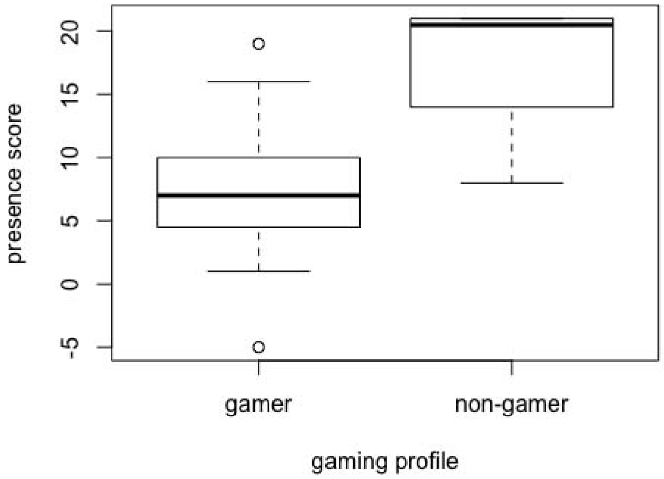


Figure 7.8: UCAVE Study IV - Presence score is higher for participants who self-reported their gaming profile (gprofile) as non-gamers.

ther immersive or non-immersive user interface control schematics. During the course of solving the maze, the participants had the option of verbally communicating with the study investigator in case they needed any further information.

The maze task model consisted of three tasks, all of which involve wayfinding. These tasks were as follows:

1. Find your way to target 1, a mini map ( 7.5b)
2. Find your way to target 2, the animated human avatar ( 7.5a)
3. Find your way back to the entrance of the maze

The difference between immersive and non-immersive user interface lies in the way the participants controlled their gaze. Immersive user interface control meant that the

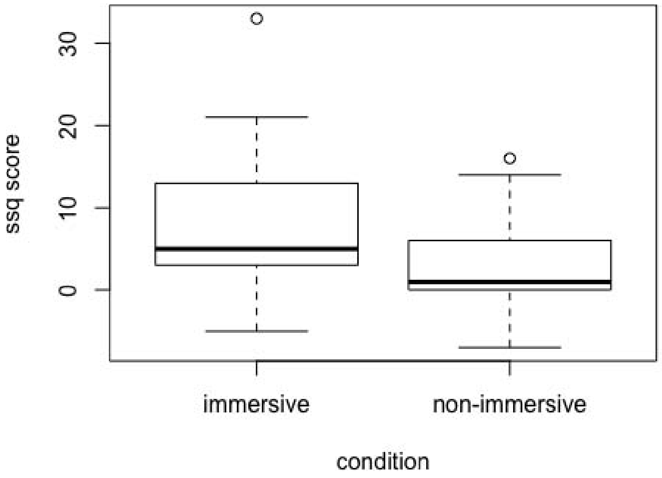


Figure 7.9: UCAVE Study IV - SSQ score is higher in immersive mode of avatar control.

participants used their natural head orientation to align their view inside the maze environment (VE). Non-immersive user interface control meant the participants had to control their view inside the maze using the joystick analog control on the gaming controller (gamepad) (Figure 7.1). The participants were required to be seated while going through the study because this configuration helped minimize simulator sickness. After completing their first session, the participants were given a break of 5 minutes before starting their next session to help normalize any fatigue conditions. In their second session, they were given the same maze once again but with a different user interface control schematic from before. Upon completion of their second session, the post-experience survey was administered, which included a presence questionnaire [Usoh et al., 2000] along with personal feedback. Simulator sickness questionnaires [Kennedy et al., 1993] were provided contextually in-between the sessions. At this point, all participant activity have been logged, collated and uploaded for further analysis.

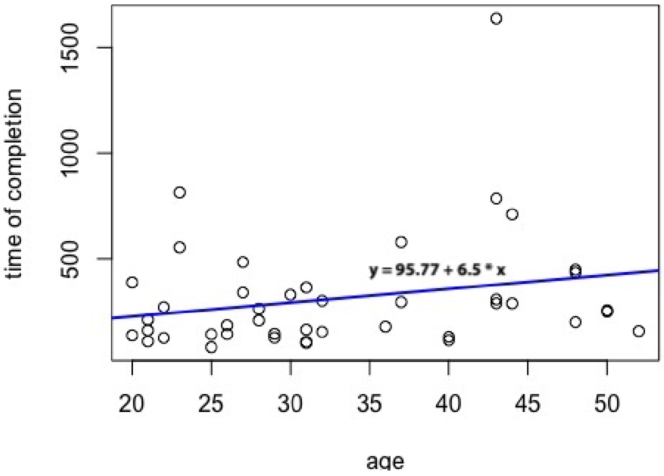


Figure 7.10: UCAVE Study IV - Graph showing scatterplot of time of completion of the maze as the y-axis and age of the participants as the x-axis.

## 7.5 Results

Only 19 participants out of 40 completed both maze sessions. We report that 2 participants out of 40 were not appropriately logged due to device I/O failure, resulting in complete data loss of 2 data points from the analysis. We investigate our dependent variable (time of completion) against the set of independent variables such as the participant's gaming profile type (gamer or non-gamer), the type of deployment (immersive and non-immersive), presence score, simulator sickness score, age, and gender.

We report a significant difference between groups of means of gaming profile type and time of completion (F-value = 12.885, P = 0.000914). The box plot of time of completion with respect to gaming profile [see Figure 7.7] illustrates the difference between gamer and non-gamer groups. We observe, a majority of gamer participants took less time in

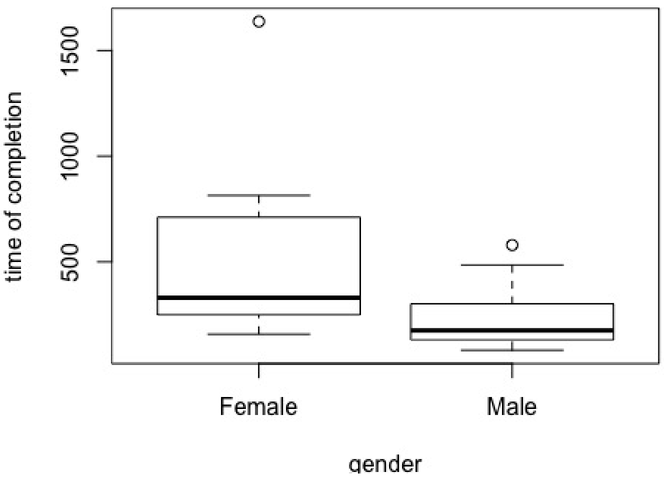
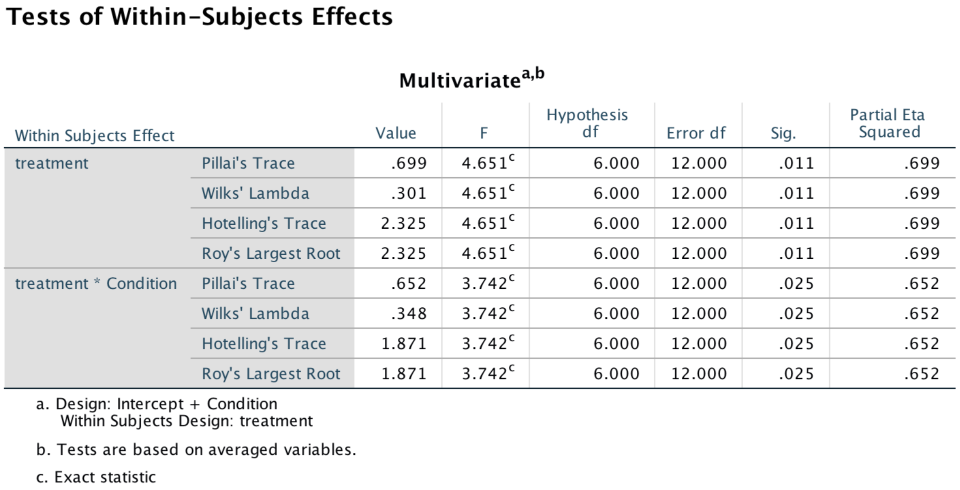


Figure 7.11: UCAVE Study IV - Boxplot showing time of completion of the maze by group (gender).

solving the maze on average, whereas a majority of non-gamer participants took more time. Furthermore, figure 7.10 shows a positive correlation (scatterplot) between the time of completion of the maze (in seconds) and the age of the participants. We also report that female participants in this study spent higher time completing the maze on average than the male participants in this study [see Figure 7.11]. This suggests that there is a trend of age and gender together impacting immersive VR user performance.

Additionally, we report a significant difference between groups of means of gaming profile type and self-reported presence score of the successful participants (F-value = 9.565, P = 0.00699). The box plot of presence score with respect to gaming profile [see Figure 7.8] illustrates the difference between gamer and non-gamer groups. Interestingly, we observed another significant difference between groups of means of condition of deployment and the self reported SSQ scores [see Figure 7.9]. It is indicative of the fact



**Tests of Within-Subjects Effects**

**Multivariate**$^{a,b}$

| Within Subjects Effect | | Value | F | Hypothesis df | Error df | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| treatment | Pillai's Trace | .699 | 4.651$^{c}$ | 6.000 | 12.000 | .011 | .699 |
| | Wilks' Lambda | .301 | 4.651$^{c}$ | 6.000 | 12.000 | .011 | .699 |
| | Hotelling's Trace | 2.325 | 4.651$^{c}$ | 6.000 | 12.000 | .011 | .699 |
| | Roy's Largest Root | 2.325 | 4.651$^{c}$ | 6.000 | 12.000 | .011 | .699 |
| treatment * Condition | Pillai's Trace | .652 | 3.742$^{c}$ | 6.000 | 12.000 | .025 | .652 |
| | Wilks' Lambda | .348 | 3.742$^{c}$ | 6.000 | 12.000 | .025 | .652 |
| | Hotelling's Trace | 1.871 | 3.742$^{c}$ | 6.000 | 12.000 | .025 | .652 |
| | Roy's Largest Root | 1.871 | 3.742$^{c}$ | 6.000 | 12.000 | .025 | .652 |

a. Design: Intercept + Condition
Within Subjects Design: treatment

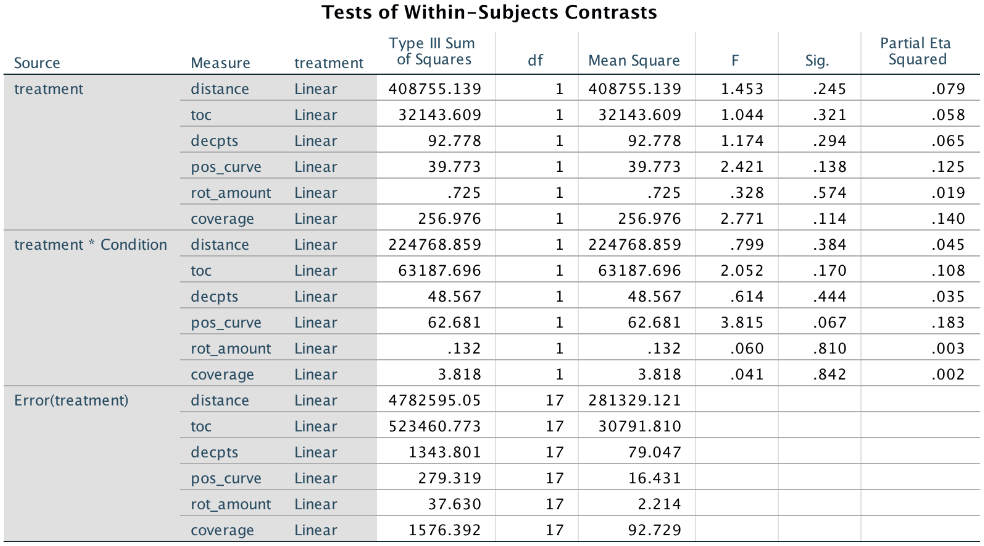
b. Tests are based on averaged variables.

c. Exact statistic

Figure 7.12: Repeated measures analysis for User Study IV; test of within-subjects effects.

that immersive user interface control made participants nauseated to a higher degree than non-immersive user interface control. All of these findings together are indicative of a trend, but we need inferential statistics to make an argument conclusively. We then proceed to explore our recorded user trajectory dataset.

Repeated measures analysis of the user trajectory dataset revealed that technical factors, such as immersive and non-immersive user interfaces, do significantly impact immersive VR user performance [see Figure 7.13 and Figure 7.12]. This shows a significant main effect of treatment (difference between immersive and non-immersive user interface) and an interactive effect of treatment and condition (i.e. order of deployment; immersive or non-immersive first, immersive or non-immersive second) combined. We find that condition is not a significant factor between subjects. Looking closely at indi-



**Tests of Within-Subjects Contrasts**

| Source | Measure | treatment | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|---|
| treatment | distance | Linear | 408755.139 | 1 | 408755.139 | 1.453 | .245 | .079 |
| | toc | Linear | 32143.609 | 1 | 32143.609 | 1.044 | .321 | .058 |
| | decpts | Linear | 92.778 | 1 | 92.778 | 1.174 | .294 | .065 |
| | pos_curve | Linear | 39.773 | 1 | 39.773 | 2.421 | .138 | .125 |
| | rot_amount | Linear | .725 | 1 | .725 | .328 | .574 | .019 |
| | coverage | Linear | 256.976 | 1 | 256.976 | 2.771 | .114 | .140 |
| treatment * Condition | distance | Linear | 224768.859 | 1 | 224768.859 | .799 | .384 | .045 |
| | toc | Linear | 63187.696 | 1 | 63187.696 | 2.052 | .170 | .108 |
| | decpts | Linear | 48.567 | 1 | 48.567 | .614 | .444 | .035 |
| | pos_curve | Linear | 62.681 | 1 | 62.681 | 3.815 | .067 | .183 |
| | rot_amount | Linear | .132 | 1 | .132 | .060 | .810 | .003 |
| | coverage | Linear | 3.818 | 1 | 3.818 | .041 | .842 | .002 |
| Error(treatment) | distance | Linear | 4782595.05 | 17 | 281329.121 | | | |
| | toc | Linear | 523460.773 | 17 | 30791.810 | | | |
| | decpts | Linear | 1343.801 | 17 | 79.047 | | | |
| | pos_curve | Linear | 279.319 | 17 | 16.431 | | | |
| | rot_amount | Linear | 37.630 | 17 | 2.214 | | | |
| | coverage | Linear | 1576.392 | 17 | 92.729 | | | |

Figure 7.13: Repeated measures analysis for User Study IV; test of within-subjects contrast.

vidual measures, we don't find a difference on any particular measure [see Figure 7.13]. This suggests small but consistent differences that arise as a result of treatment (immersive versus non-immersive user interface).

## 7.6 Discussion

We *reject* our null hypothesis and accept the alternate hypothesis. We found that prior exposure to video-gaming, age, and gender has a measurable impact on immersive VR user performance. While conceptualizing our experimental design, there were concerns about choosing the appropriate measurement parameters as performance metric for VR tasks, we worried that the immersive and non-immersive user interface control paradigms

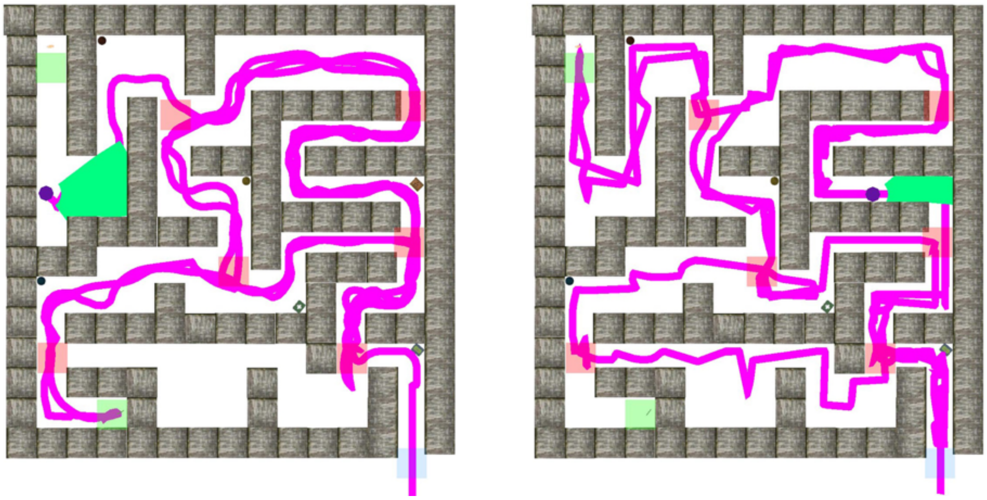
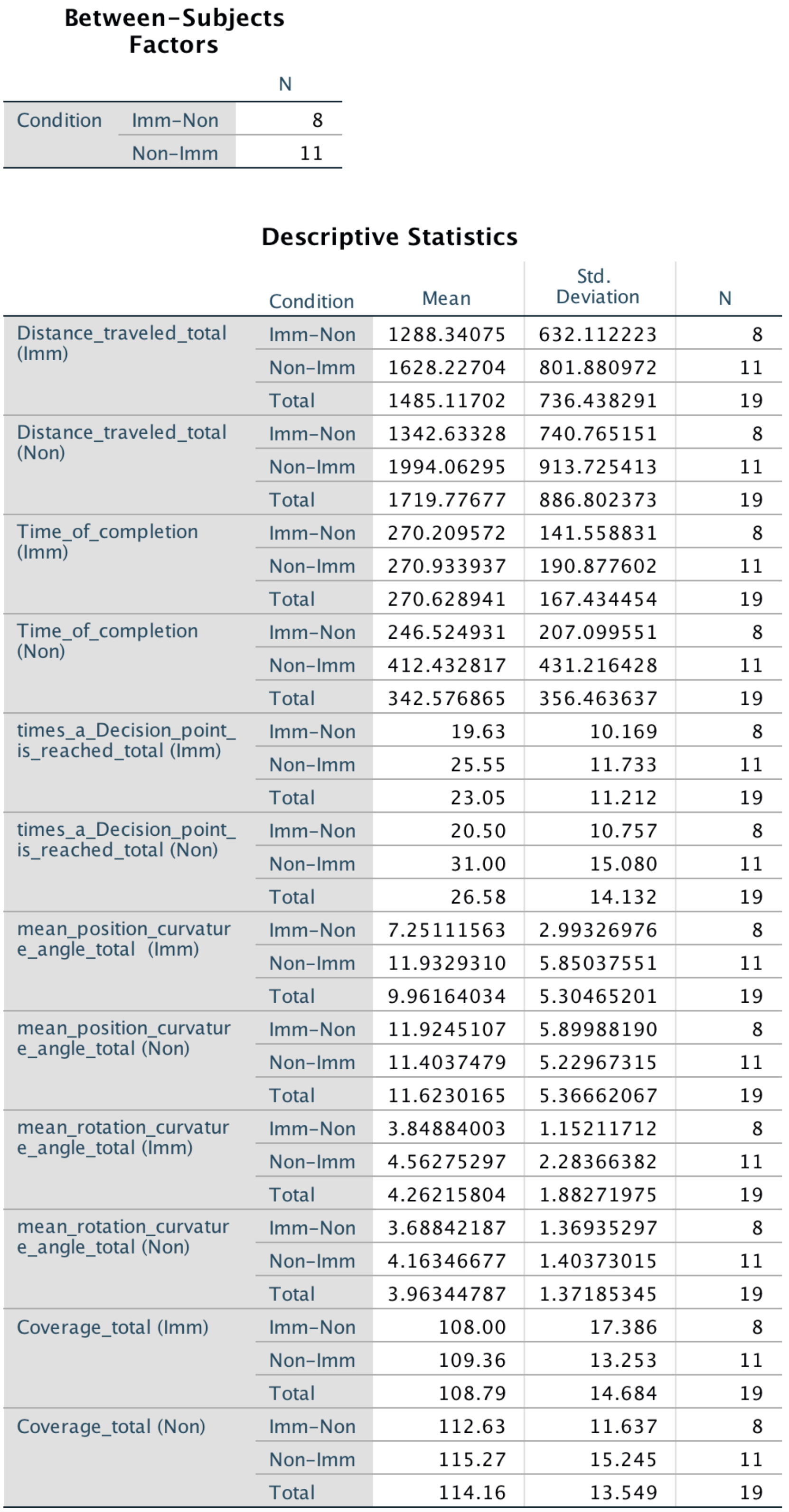


Figure 7.14: Visual comparison of user trajectories of a randomly selected gamer (left) and a non-gamer (right) while solving the maze in the non-immersive interface.

would be confusing to users, and that visual cues to understand decision making in mazes during analysis would be complicated and confounding. During the course of the study, we observed that users, who claimed to be self-perceived video-gamers, aren't confused by the immersive, non-immersive interface control paradigm. The video-gaming group seemed to treat both immersive and non-immersive user interface as the same, unlike the non-video-gaming group. The ability to replay user trajectory in the Unity game engine's editor environment proved to be very useful. These visual replays helped us determine user trajectory features such as, curvature, and head-rotation amount [see Figure 7.6] to analyze.

**Additional findings**: The interface worked well except twice when it failed to record the session due to a device malfunction. Due to the minimalist nature of our system setup, we were able to reduce points of failure in our system so that our participants could focus better on the study objectives. All user data logging was done in the background and were stored locally on-board the HMD device for faster I/O. The maze provided ample space-time interactivity for the participants which in turn provided us a rich data set including high resolution user trajectory data which can be parsed through in real-time [see Figure 7.4]. The task model in our study also proved to be fairly difficult for most of the participants, which helped offset the balance between chance-based decisions and skill-based decisions inside the maze. The average time that the users spent in immersive interface was 268 seconds while the average time spent by the same users in non-immersive interface was 364 seconds. As suspected, there were differences in performance between the gamer and the non-gamer groups [see Figure 7.14]. In the context of spatial problem-solving, wayfinding, the combined finding of simulator sickness and presence score could be indicative of the fact that the two groups approached the study differently. From a pedagogical point of view, if immersive VR applications were to be deployed while making a meaningful impact to its user's skill-building exercise, we would have to account for the factor that different groups of users conceive and treat immersive environments differently based on their prior experience. Standardized immersive experience, although logistically good, is not effective in targeting individual specific needs.

To summarize, in this study, we have showed that prior exposure to video-gaming, age, and gender is found to have a measurable impact on user performance when it comes to spatial maze navigation in immersive VR. We conducted extended analysis on recorded user trajectory data. To that end, we defined a set of mathematically derived features generalized for each trajectory such as distance traveled, decision points reached inside the maze, positional curvature, head rotation amount, and coverage of the maze. Upon closer inspection of the variation in these trajectory features through repeated measure analysis, we found a small but consistent difference that arises as a result of the treatment of our final study design, that is immersive versus non-immersive user interface. We find that immersive user interface helps users explore the VE more with natural head gaze control than the non-immersive user interface with analog gaze control.



**Between-Subjects Factors**

| | | N |
|---|---|---|
| Condition | Imm-Non | 8 |
| | Non-Imm | 11 |

**Descriptive Statistics**

| | Condition | Mean | Std. Deviation | N |
|---|---|---|---|---|
| Distance_traveled_total (Imm) | Imm-Non | 1288.34075 | 632.112223 | 8 |
| | Non-Imm | 1628.22704 | 801.880972 | 11 |
| | Total | 1485.11702 | 736.438291 | 19 |
| Distance_traveled_total (Non) | Imm-Non | 1342.63328 | 740.765151 | 8 |
| | Non-Imm | 1994.06295 | 913.725413 | 11 |
| | Total | 1719.77677 | 886.802373 | 19 |
| Time_of_completion (Imm) | Imm-Non | 270.209572 | 141.558831 | 8 |
| | Non-Imm | 270.933937 | 190.877602 | 11 |
| | Total | 270.628941 | 167.434454 | 19 |
| Time_of_completion (Non) | Imm-Non | 246.524931 | 207.099551 | 8 |
| | Non-Imm | 412.432817 | 431.216428 | 11 |
| | Total | 342.576865 | 356.463637 | 19 |
| times_a_Decision_point_is_reached_total (Imm) | Imm-Non | 19.63 | 10.169 | 8 |
| | Non-Imm | 25.55 | 11.733 | 11 |
| | Total | 23.05 | 11.212 | 19 |
| times_a_Decision_point_is_reached_total (Non) | Imm-Non | 20.50 | 10.757 | 8 |
| | Non-Imm | 31.00 | 15.080 | 11 |
| | Total | 26.58 | 14.132 | 19 |
| mean_position_curvature_angle_total (Imm) | Imm-Non | 7.25111563 | 2.99326976 | 8 |
| | Non-Imm | 11.9329310 | 5.85037551 | 11 |
| | Total | 9.96164034 | 5.30465201 | 19 |
| mean_position_curvature_angle_total (Non) | Imm-Non | 11.9245107 | 5.89988190 | 8 |
| | Non-Imm | 11.4037479 | 5.22967315 | 11 |
| | Total | 11.6230165 | 5.36662067 | 19 |
| mean_rotation_curvature_angle_total (Imm) | Imm-Non | 3.84884003 | 1.15211712 | 8 |
| | Non-Imm | 4.56275297 | 2.28366382 | 11 |
| | Total | 4.26215804 | 1.88271975 | 19 |
| mean_rotation_curvature_angle_total (Non) | Imm-Non | 3.68842187 | 1.36935297 | 8 |
| | Non-Imm | 4.16346677 | 1.40373015 | 11 |
| | Total | 3.96344787 | 1.37185345 | 19 |
| Coverage_total (Imm) | Imm-Non | 108.00 | 17.386 | 8 |
| | Non-Imm | 109.36 | 13.253 | 11 |
| | Total | 108.79 | 14.684 | 19 |
| Coverage_total (Non) | Imm-Non | 112.63 | 11.637 | 8 |
| | Non-Imm | 115.27 | 15.245 | 11 |
| | Total | 114.16 | 13.549 | 19 |

Figure 7.15: Descriptive statistics for all potential features impacting user performance in User Study IV.

# Chapter 8

# Summary and Future Directions

*"Every great advance in science has issued from a new audacity of imagination."*

— John Dewey, The Quest for Certainty, 1929

Immersive VR applications have been traditionally deployed in a controlled laboratory setting ever since the advent of HMDs [Sutherland, 1968]. With the proliferation of highly accessible mobile communication devices such as the smartphone, high pixel density display technology became available as an alternative to dedicated and tethered HMDs. The mobility of these smart devices inspired us to conceive a mobile VR platform that is untethered and can be deployed universally. Our work represents another step toward ubiquitous deployment of immersive virtual experiences which will potentially advance general VR usability, incite more research, and further the cause for practical VR applications.

## 8.1 Review of results

In this dissertation, we claimed that:

*Due to an increased prevalence of ubiquitous VR systems circa 2011 through the democratization of consumer technology, we need to design and evaluate comprehensive, immersive ubiquitous VR experiences that acknowledge the existing usability bias amongst immersive VR users. Furthermore, we need to understand better how extrinsic factors play a role in affecting user performance in an immersive VR experience using such ubiquitous VR systems.*

This dissertation introduced a ubiquitous VR platform called the Ubiquitous Collaborative Activity Virtual Environment (UCAVE) [see chapter 3] engineered to deploy immersive VEs that leverage mobile communication platforms (smartphones) as displays and motion trackers as input devices. We went through three iterations of system design incrementally adding features such as six degrees of freedom (6DOF) hand tracking, wearable belt design, and 3D printed visors. We demonstrated a ubiquitous VR system that could be put together using consumer-grade technology quite inexpensively. Next, we showed over the course of four formative user studies how to conduct field VR studies with our UCAVE platform by going to a potential user population located at various locations spread across university campuses. Such field studies have never been possible before to conduct outside the laboratory setting as infrastructural footprint and deployment cost with the traditional VR setup is high. Study participants solve and are evaluated on, immersive VR task performance for a specific kind of spatial navigation task, that is maze navigation, through interaction with our UCAVE platform. We collected participants' trajectory data and qualitative measures such as demographic information. We further analyzed the resulting trajectory dataset to find trends in spatial behaviorism amongst study participants. The four studies were categorized as ergonomic [see chapter 4], environmental [see chapter 5], human [see chapter 6], and technical [see chapter 7] factors and their impact on immersive VR user performance. Furthermore, we explored and reported the core impact of immersion through HMDs on immersive VR user performance and spatial navigation behavior. Over the span of four user studies, we ran a total of 216 participants who volunteered to partake in our immersive VR maze experience.

### 8.1.1 Summary of study findings

In Study I (a study of ergonomic factor), we showed that having an untethered immersive VR setup promotes better user performance (shorter time of completion of maze) when it comes to spatial maze navigation in immersive VR. The Study I design involved an adaptation of the famous motion picture (The Matrix™) in the context of the immersive task model, which we believe acted as a cultural frame of reference for our participants. We found that the difference in mean total time spent in the maze experience was lower for the untethered group by a margin of 3 minutes, which supports our hypothesis that an untethered immersive VR setup is desirable. Removing a layer of physical constraint such as being tethered to HMDs is not only a matter of logistical simplicity, but we believe it also reflects user comfort when it comes to having an immersive virtual experience. Being tethered or not should be considered a deployment configuration closely tied to the immersive VR task model. If the objective of any VR experience is to navigate relatively large VEs with a lot of head rotation involved in search related tasks, we find having an untethered VR deployment configuration is desirable for users.

With Study II (a study of environmental factor), we showed that having a matched deployment configuration between outdoor VE and outdoor physical environment results in the best user performance (higher raw score) in an immersive VR experience than any other configuration. Study II design involved a First-person shooter (FPS) experience with each participant playing two distinct levels with the one type of VE being an outdoor place (urban setting) and the other VE being an indoor place (warehouse setting). We found that the type of VE compounded with the matched versus unmatched deployment configuration affects users' ability to score in an FPS experience. We can conjecture that matching the physical context to the virtual would aid in immersive VR performance, but to thoroughly verify this claim, one needs to consider the domain expertise of psychology which is beyond the scope of the current study. If the objective of any VR experience is to focus on any task rather than the VE, we ultimately believe that maintaining the continuum of the physical and the VE should lower the cognitive load (otherwise busy processing the difference between the physical environment and the VE) of immersive VR users and potentially aid in improving user performance.

In Study III (a study of human factor), we showed that better athletic ability (via self-perceived reporting) does not affect user performance when it comes to spatial maze navigation in immersive VR. Study III design involved a simplified maze (simpler than Study I) with no reference to popular media but rather focused around the idea of an altruistic theme. The goal of the maze experience was to find and rescue Uga, the mascot of the University of Georgia Bulldogs. We adopted a more straightforward hardware setup for Study III which involved a commercially available HMD with a smartphone as the display and a wireless game-controller for logistical simplicity. We found that there is no significant impact on the users' performance based on their self-reported physical activity score. However, the users' gaming profile does seem to affect significantly immersive VR performance (time of completion of the maze). Gaming profile coupled with age and gender seem to indicate that young male participants who are self-reported gamers tend to solve the maze faster than the rest of the population. Familiarity to input devices such as Gamepads and exposure to video games helps gamers over non-gamers to navigate VEs faster. If the objective of any VR experience is to navigate larger VEs with emphasis on spatial navigational skill building, we believe a more generalized input schematic should balance the familiarity bias. The level of complexity of the immersive VR task model was another contributing factor to users taking random chances in their maze navigational ability. If the task model is relatively simple, the occurrence in random chances are hard to discern from actual maze navigability. We find that attaining a balance between the immersive VR task model complexity and exposure time to immersive VR applications is very important from VR design standpoint.

With Study IV (a study of technical factor), we showed that prior exposure to video-gaming, age, and gender is found to have a measurable impact on user performance when it comes to spatial maze navigation in immersive VR. Study IV design involved a relatively complicated maze design than Study III. The context of the maze experience was similar to Study III, in which the subject is required to find and rescue another human (avatar). The task included finding a clue (minimap) before finding the human avatar and then tracing back the path to the entrance of the maze. The hardware setup for Study IV was kept similar to Study III for maintaining consistency. Study IV design also looked at each participant partaking the maze experience twice with the distinction that one of the session would require the user to use only the game-controller to navigate the maze while the other would involve the same user solving the same maze combining natural head gaze rotation and the game-controller to navigate the maze. We found that the gaming profile coupled with age and gender is proving to be a strong indicator of success when it comes to navigating immersive mazes in VR. After our preliminary finding, we focused on the important issue of exploring the core impact on user task performance in an immersive VR setup deployed under an immersive setting. We conducted extended analysis on recorded user trajectory data. To that end, we defined a set of mathematically derived features generalized for each trajectory such as distance traveled, decision points reached inside the maze, positional curvature, head rotation amount, and coverage of the maze. Upon closer inspection of the variation in these trajectory features through repeated measure analysis, we found a small but consistent difference that arises as a result of the treatment of our final study design, that is immersive versus non-immersive user interface. We find that immersive user interface helps users explore the VE better with natural head gaze control than the non-immersive user interface with analog gaze control. These findings are useful to VR designers in making appropriate trade-offs in VR level design for specific VR applications.

Given all of our findings, we conclude that deployment of immersive VR experiences through consumer grade HMDs as display and a wireless controller as an input device scales well as a VR hardware configuration to conducting field VR studies. Furthermore, having an untethered, contextually matched deployment configuration (outdoor-outside) aids immersive VR user performance. Lastly, VR users who are younger, predominantly males, and who are exposed to video-gaming, tend to perform better in immersive VR when the task is about maze navigation. While our results point out several factors that may affect immersive VR user performance or acceptance of ubiquitous VR, ultimately the actual use of ubiquitous VR will be determined by many more factors such as how well the metaphor employed maps to the real space, or how sickening the immersive VR experience is. Frameworks such as the Technology Acceptance Model (TAM) [Davis et al., 1989] help designers determine what factors might be more or less necessary for a practical application. As such, our results are only a start to a much broader discussion about what forms may be suitable for ubiquitous VR.

## 8.2 Future work

The contributions of this work have an immediate impact—immersive VR applications can be deployed in an unconstrained fashion with better accessibility to a larger population at a fraction of cost as compared to traditional VR setup.

### 8.2.1 Reducing cybersickness

One of the current barriers to widespread acceptance of VR technology has been primarily the issue of Cybersickness. Cybersickness exhibits symptoms that parallel symptoms of classical motion sickness [LaViola Jr, 2000]. We believe that having a light-weight VR apparatus such as the UCAVE system helps in solving the weight encumbrance issue. We plan to explore the variation in Cybersickness in future study design based on various configurations such as weight, the complexity of user task model, and amount of head rotation involved in an immersive VR experience.

### 8.2.2 Tracking spatial navigability

Whether or not going through an immersive virtual experience of maze navigation helps users to be better navigators of mazes is an important research question. We believe having a light-weight VR apparatus such as the UCAVE system allows users to focus more on the spatial navigation task by lessening their cognitive load due to other extrinsic factors. To be able to track the subsequent progress of users ability to navigate mazes, a longitudinal study design is needed. We plan to explore the progress of spatial navigability skill in future study design based on varying complexity of mazes ranging from easy to hard.

### 8.2.3 Reducing usability bias

We have observed in our Study IV [see Chapter 7] that prior video-gaming experience has a dominant effect on user performance when it comes to spatial maze navigation using gamepads or game-controllers. We believe that this effect is prominent mainly due to the high familiarity of VR input device such as the game-controllers. We plan to explore other input devices which are less familiar as a gaming input device in the hope of normalizing the existing gaming bias amongst VR users.

## 8.3 Closing remarks

The application of untethered, ubiquitous VR experiences is far-reaching. By minimizing the logistical footprint of deploying immersive VR experiences and successfully deploying a suite of formative user studies through the use of our UCAVE platform, we believe that we have revisited Pausch's work [Pausch, 1991b] to practically demonstrate the usability issues of a ubiquitous VR platform. The current democratization of VR technology was made possible by the advances in smartphone technology circa 2011. The smartphones with their high pixel density displays were apt for a self-contained light-weight HMD design. The shift in HMD design made it feasible to deploy immersive VR experiences ubiquitously and marked the first step towards realizing ubiquitous VR experiences. The next step is developing an input schematic that is generalized and normalizes existing video gaming biases. True pedagogically valid immersive experiences need a universal VR framework that can scale well with the number of users and that supports a wide array of input devices and displays. For immersive VR to become genuinely essential, it has to become invisible much like electricity and effortless in the interface, so that its users can solely concentrate on the skill-building exercises that VR has to offer.

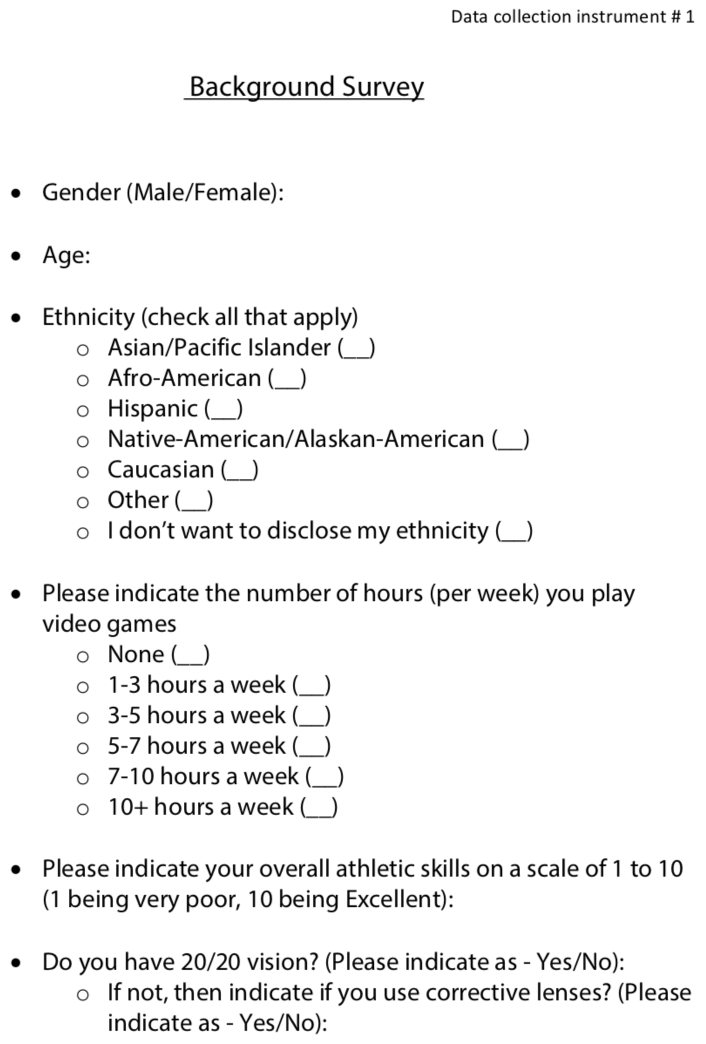
Our studies and data show the existence of a stark usability barrier to using VR technology based on the familiarity of input devices, exposure to video-gaming, age, and gender. Video gamers who are young and predominantly males tend to perform better than the rest of the study population. We hope that our experimental design and data will serve as a benchmark for the next generation of VR engineers, designers and developers. Ultimately, the hope is that this work will enable the widespread deployment of immersive VR experiences making VR useful.

# Appendix A

# Surveys

Table A.1: Pre-experience and post-experience survey

| Survey Question | Response type |
|---|---|
| Please indicate the number of hours (per week) you play video games | Ordinal,<br>1 (1-3 hours) …<br>5 (10+ hours) |
| Please indicate your overall (perceived) athletic skills | Ordinal,<br>1 (Very poor) …<br>10 (Excellent) |
| Please indicate your response to the questions related to playing video games | Ordinal,<br>Yes/No/Maybe |
| Please indicate and rate any of the symptoms listed in the table below on a scale of 1 to 10 (SSQ) | Ordinal,<br>1 (Never felt) …<br>10 (Str. felt) |
| Please rate your agreement with the following statements w.r.t. both the VR sessions witnessed (Presence) | Likert,<br>-3 (Str. Disagree) …<br>+3 (Str. Agree) |
| Briefly tell us about your virtual experiences (suggestions/comments) | Free Response |
| Extended comments/suggestions | Free Response |

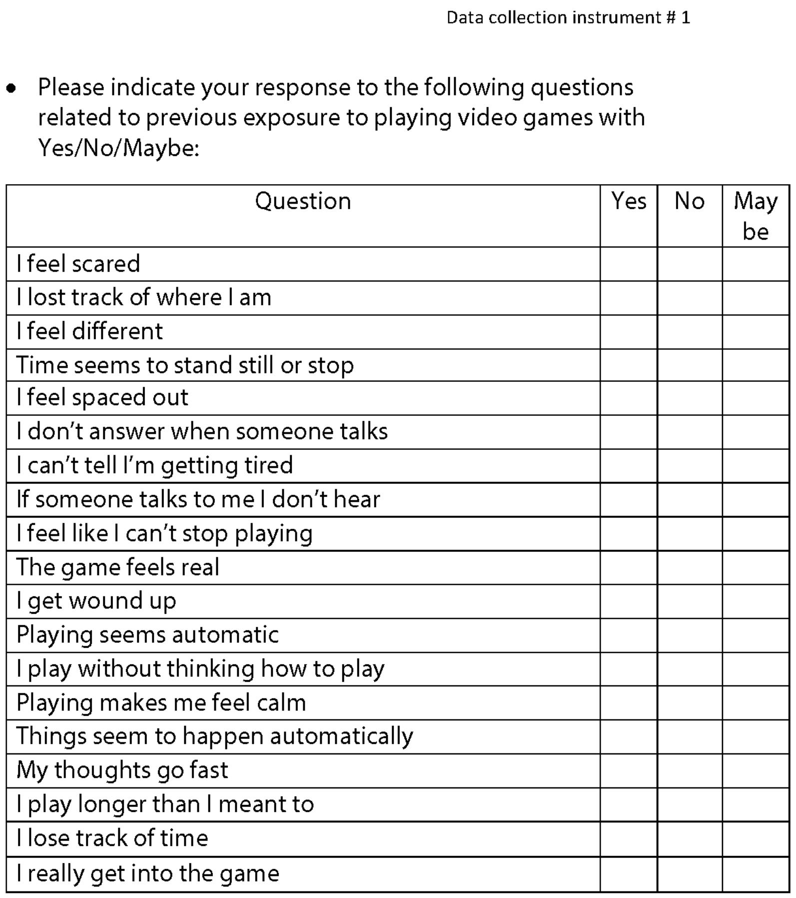


Data collection instrument # 1

Background Survey

- Gender (Male/Female):
- Age:
- Ethnicity (check all that apply)
    - Asian/Pacific Islander (__)
    - Afro-American (__)
    - Hispanic (__)
    - Native-American/Alaskan-American (__)
    - Caucasian (__)
    - Other (__)
    - I don't want to disclose my ethnicity (__)
- Please indicate the number of hours (per week) you play video games
    - None (__)
    - 1-3 hours a week (__)
    - 3-5 hours a week (__)
    - 5-7 hours a week (__)
    - 7-10 hours a week (__)
    - 10+ hours a week (__)
- Please indicate your overall athletic skills on a scale of 1 to 10 (1 being very poor, 10 being Excellent):
- Do you have 20/20 vision? (Please indicate as - Yes/No):
    - If not, then indicate if you use corrective lenses? (Please indicate as - Yes/No):

Figure A.1: The UCAVE Study I-IV Background survey questionnaire

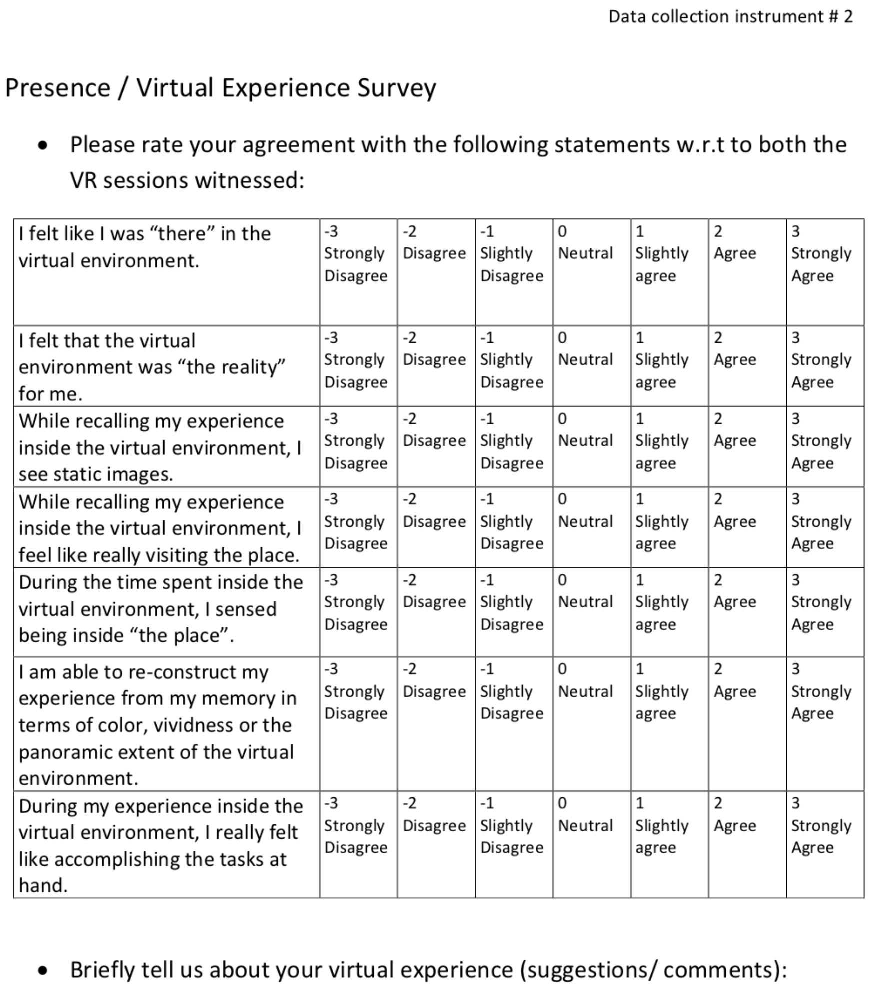


Data collection instrument # 1

- Please indicate your response to the following questions related to previous exposure to playing video games with Yes/No/Maybe:

| Question | Yes | No | May be |
|---|---|---|---|
| I feel scared | | | |
| I lost track of where I am | | | |
| I feel different | | | |
| Time seems to stand still or stop | | | |
| I feel spaced out | | | |
| I don't answer when someone talks | | | |
| I can't tell I'm getting tired | | | |
| If someone talks to me I don't hear | | | |
| I feel like I can't stop playing | | | |
| The game feels real | | | |
| I get wound up | | | |
| Playing seems automatic | | | |
| I play without thinking how to play | | | |
| Playing makes me feel calm | | | |
| Things seem to happen automatically | | | |
| My thoughts go fast | | | |
| I play longer than I meant to | | | |
| I lose track of time | | | |
| I really get into the game | | | |

Figure A.2: The UCAVE Study IV Gaming profile assessment questionnaire



Data collection instrument # 2

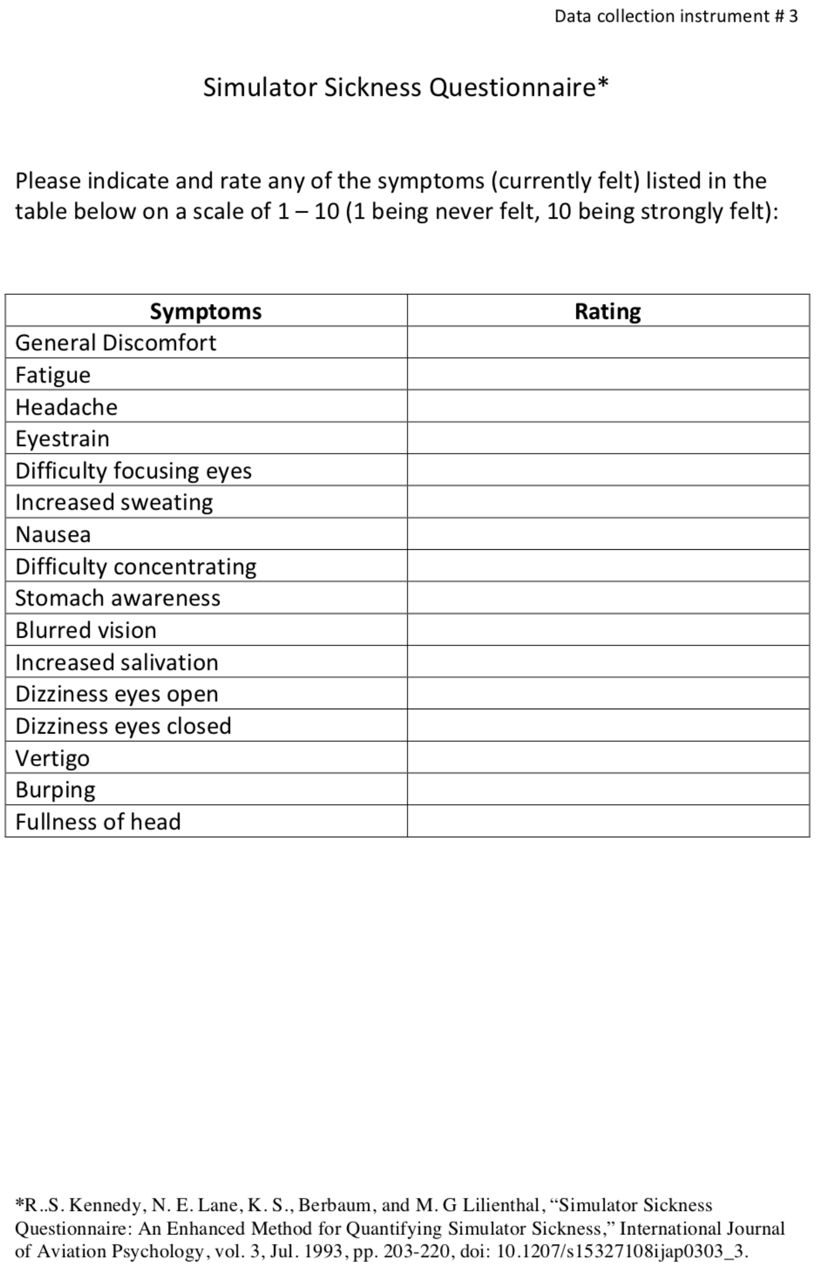
## Presence / Virtual Experience Survey

- Please rate your agreement with the following statements w.r.t to both the VR sessions witnessed:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| I felt like I was "there" in the virtual environment. | -3 Strongly Disagree | -2 Disagree | -1 Slightly Disagree | 0 Neutral | 1 Slightly agree | 2 Agree | 3 Strongly Agree |
| I felt that the virtual environment was "the reality" for me. | -3 Strongly Disagree | -2 Disagree | -1 Slightly Disagree | 0 Neutral | 1 Slightly agree | 2 Agree | 3 Strongly Agree |
| While recalling my experience inside the virtual environment, I see static images. | -3 Strongly Disagree | -2 Disagree | -1 Slightly Disagree | 0 Neutral | 1 Slightly agree | 2 Agree | 3 Strongly Agree |
| While recalling my experience inside the virtual environment, I feel like really visiting the place. | -3 Strongly Disagree | -2 Disagree | -1 Slightly Disagree | 0 Neutral | 1 Slightly agree | 2 Agree | 3 Strongly Agree |
| During the time spent inside the virtual environment, I sensed being inside "the place". | -3 Strongly Disagree | -2 Disagree | -1 Slightly Disagree | 0 Neutral | 1 Slightly agree | 2 Agree | 3 Strongly Agree |
| I am able to re-construct my experience from my memory in terms of color, vividness or the panoramic extent of the virtual environment. | -3 Strongly Disagree | -2 Disagree | -1 Slightly Disagree | 0 Neutral | 1 Slightly agree | 2 Agree | 3 Strongly Agree |
| During my experience inside the virtual environment, I really felt like accomplishing the tasks at hand. | -3 Strongly Disagree | -2 Disagree | -1 Slightly Disagree | 0 Neutral | 1 Slightly agree | 2 Agree | 3 Strongly Agree |

- Briefly tell us about your virtual experience (suggestions/ comments):

Figure A.3: Presence evaluation questionnaire



Data collection instrument # 3

Simulator Sickness Questionnaire*

Please indicate and rate any of the symptoms (currently felt) listed in the table below on a scale of 1 – 10 (1 being never felt, 10 being strongly felt):

| **Symptoms** | **Rating** |
|---|---|
| General Discomfort | |
| Fatigue | |
| Headache | |
| Eyestrain | |
| Difficulty focusing eyes | |
| Increased sweating | |
| Nausea | |
| Difficulty concentrating | |
| Stomach awareness | |
| Blurred vision | |
| Increased salivation | |
| Dizziness eyes open | |
| Dizziness eyes closed | |
| Vertigo | |
| Burping | |
| Fullness of head | |

*R..S. Kennedy, N. E. Lane, K. S., Berbaum, and M. G Lilienthal, "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," International Journal of Aviation Psychology, vol. 3, Jul. 1993, pp. 203-220, doi: 10.1207/s15327108ijap0303_3.

Figure A.4: The simulator sickness assessment questionnaire

# Bibliography

Avery, B., B. H. Thomas, J. Velikovsky, and W. Piekarski

2005. Outdoor augmented reality gaming on five dollars a day. In *Proceedings of the Sixth Australasian conference on User interface-Volume 40*, Pp. 79–88. Australian Computer Society, Inc.

Basu, A., C. Ball, B. Manning, and K. Johnsen

2016. Effects of user physical fitness on performance in virtual reality. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, Pp. 233–234.

Basu, A., K. Johnsen, and K. Bogert

2013. Poster: Evolution and usability of ubiquitous immersive 3d interfaces. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, Pp. 131–132.

Basu, A., A. Raij, and K. Johnsen

2012a. Ubiquitous collaborative activity virtual environments. In *CSCW '12 Computer Supported Cooperative Work, Seattle, WA, USA, February 11-15, 2012*, Pp. 647–650.

Basu, A., C. Saupe, E. Refour, A. Raij, and K. Johnsen

2012b. Immersive 3dui on one dollar a day. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*, Pp. 97–100.

Benford, S., C. Greenhalgh, T. Rodden, and J. Pycock

2001. Collaborative virtual environments. *Communications of the ACM*, 44(7):79–85.

Bowers, J., J. O'Brien, and J. Pycock

1996. Practically accomplishing immersion: cooperation in and for virtual environments. In *Proceedings of the 1996 ACM conference on Computer supported cooperative work*, Pp. 380–389. ACM.

Bowman, D. A., E. T. Davis, L. F. Hodges, and A. N. Badre

1999. Maintaining spatial orientation during travel in an immersive virtual environment. *Presence: Teleoperators and Virtual Environments*, 8(6):618–631.

Bowman, D. A., D. Koller, and L. F. Hodges

1998a. A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual Reality*, 3(2):120–131.

Bowman, D. A., D. Koller, and L. F. Hodges

1998b. A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual Reality*, 3(2):120–131.

Cruz-Neira, C., D. J. Sandin, and T. A. DeFanti

1993. Surround-screen projection-based virtual reality: the design and implementation of the cave. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, Pp. 135–142. ACM.

Cruz-Neira, C., D. J. Sandin, T. A. DeFanti, R. V. Kenyon, and J. C. Hart

1992. The cave - audio visual experience automatic virtual environment. *Commun. ACM*, 35(6):64–72.

Davis, F. D., R. P. Bagozzi, and P. R. Warshaw

1989. User acceptance of computer technology: a comparison of two theoretical models. *Management science*, 35(8):982–1003.

DBLP

1993. Computer science bibliography. `https://dblp.uni-trier.de/`.

Drees, R. C., J. Pleiss, and R. D. Schmid

1996. Highly immersive molecular modeling (HIMM): an architecture for the integration of molecular modeling and virtual reality. In *German Conference on Bioinformatics*, Pp. 190–192.

Farella, E., D. Brunelli, M. Bonfigli, L. Benini, and B. Riccò

2003. Multi-client cooperation and wireless pda interaction in immersive virtual environment. *Proc. EUROMEDIA 2003*.

Fitzmaurice, G. W., S. Zhai, and M. H. Chignell

1993. Virtual reality for palmtop computers. *ACM Transactions on Information Systems (TOIS)*, 11(3):197–218.

Foxlin, E. and M. Harrington

2000. Weartrack: A self-referenced head and hand tracker for wearable computers and portable vr. In *Wearable Computers, The Fourth International Symposium on*, Pp. 155–162. IEEE.

Gallo, L., G. De Pietro, and I. Marra

2008. 3d interaction with volumetric medical data: experiencing the wiimote. In *Proceedings of the 1st international conference on Ambient media and systems*, P. 14. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

George, C., M. Eiband, M. Hufnagel, and H. Hussmann

2018. Trusting strangers in immersive virtual reality. In *Proceedings of the 23rd International Conference on Intelligent User Interfaces Companion, Tokyo, Japan, March 07-11, 2018*, Pp. 46:1–46:2.

Greenhalgh, C. and S. Benford

1995. Massive: a collaborative virtual environment for teleconferencing. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 2(3):239–261.

Gutiérrez, M., F. Vexo, and D. Thalmann

2004. The mobile animator: Interactive character animation in collaborative virtual environments. In *Virtual Reality, 2004. Proceedings. IEEE*, Pp. 125–284. IEEE.

Hillman, C. H., K. I. Erickson, and A. F. Kramer

2008. Be smart, exercise your heart: exercise effects on brain and cognition. *Nature reviews neuroscience*, 9(1):58.

Hindmarsh, J., M. Fraser, C. Heath, S. Benford, and C. Greenhalgh

2000. Object-focused interaction in collaborative virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 7(4):477–509.

Hodgson, E., E. R. Bachmann, D. Waller, A. Bair, and A. Oberlin

2012. Virtual reality in the wild: A self-contained and wearable simulation system. In *2012 IEEE Virtual Reality, VR 2012, Costa Mesa, CA, USA, March 4-8, 2012*, Pp. 157–158.

Huber, T., T. Wunderling, M. Paschold, H. Lang, W. Kneist, and C. Hansen

2018. Highly immersive virtual reality laparoscopy simulation: development and future aspects. *Int. J. Computer Assisted Radiology and Surgery*, 13(2):281–290.

Hutson, M. and D. Reiners

2010. Using commodity accelerometers and gyroscopes to improve speed and accuracy of janusvf. In *The Engineering Reality of Virtual Reality 2010*, volume 7525, P. 752508. International Society for Optics and Photonics.

Jeong, D. H., C. S. Lee, G. B. Jeon, C. G. Song, S. Babu, and L. Hodges

2005. Differentiation on information gathering ability in real and virtual world. In *Proceedings of Pacific Graphics*, Pp. 157–159. Citeseer.

Johnsen, K., S. J. Ahn, J. Moore, S. Brown, T. P. Robertson, A. Marable, and A. Basu

2014. Mixed reality virtual pets to reduce childhood obesity. *IEEE Transactions on Visualization and Computer Graphics*, 20(4):523–530.

Kaper, H. G. and S. Tipei

1998. Manifold compositions, music visualization, and scientific sonification in an immersive virtual-reality environment. In *Proceedings of the 1998 International Computer Music Conference, ICMC 1998, Ann Arbor, Michigan, USA, October 1-6, 1998*.

Kennedy, R. S., N. E. Lane, K. S. Berbaum, and M. G. Lilienthal

1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 3(3):203–220.

Keum, J., J. H. Ryu, Y. J. Moon, H. Cheon, N. Lee, B.-C. Bae, and J.-D. Cho

2015. Exergame development using body composition data for obesity care. In *Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in Play*, Pp. 577–582. ACM.

Koch, E. and H. Witt

2008. Prototyping a chest-worn string-based wearable input device. In *World of Wireless, Mobile and Multimedia Networks, 2008. WoWMoM 2008. 2008 International Symposium on a*, Pp. 1–6. IEEE.

Kocian, D. F.

1977. A visually-coupled airborne systems simulator (vcass)-an approach to visual simulation. Technical report, AIR FORCE AEROSPACE MEDICAL RESEARCH LAB WRIGHT-PATTERSON AFB OH.

Kossyk, I., J. Dörr, L. Raschendorfer, and K. Kondak

2011. Usability of a virtual reality system based on a wearable haptic interface. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2011, San Francisco, CA, USA, September 25-30, 2011*, Pp. 3474–3479.

LaViola Jr, J. J.

2000. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32(1):47–56.

LaViola Jr, J. J.

2008. Bringing vr and spatial 3d interaction to the masses through video games. *IEEE Computer Graphics and Applications*, 28(5).

LaViola Jr, J. J., E. Kruijff, R. P. McMahan, D. Bowman, and I. P. Poupyrev

2017. *3D user interfaces: theory and practice*. Addison-Wesley Professional.

Lee, J. C.

2008. Hacking the nintendo wii remote. *IEEE pervasive computing*, 7(3).

Leigh, J., A. Johnson, and T. A. DeFanti

1997. Cavern: A distributed architecture for supporting scalable persistence and interoperability in collaborative virtual environments. *Virtual Reality: Research, Development and Applications*, 2(2):217–237.

Lu[1], C., C. Disselkoen, L. Butler, M. Rosenberg, and J. Vance

. A virtual environment for studying immersion with low-cost interaction devices.

Macedonia, M.

2007. Generation 3d: Living in virtual worlds. *Computer*, 40(10).

Miguel, M. M., T. Ogawa, K. Kiyokawa, and H. Takemura

2007. A pda-based see-through interface within an immersive environment. In *Artificial Reality and Telexistence, 17th International Conference on*, Pp. 113–118. IEEE.

Mistry, P., P. Maes, and L. Chang

2009. Wuw-wear ur world: a wearable gestural interface. In *CHI'09 extended abstracts on Human factors in computing systems*, Pp. 4111–4116. ACM.

Norman, D. A.

1986. Cognitive engineering. *User centered system design*, 31:61.

Olson, J. L., D. M. Krum, E. A. Suma, and M. Bolas

2011. A design for a smartphone-based head mounted display. In *Virtual Reality Conference (VR), 2011 IEEE*, Pp. 233–234. IEEE.

Pausch, R.

1991a. Virtual reality on five dollars a day. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '91, Pp. 265–270, New York, NY, USA. ACM.

Pausch, R.

1991b. Virtual reality on five dollars a day. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, Pp. 265–270. ACM.

Pausch, R., M. A. Shackelford, and D. Proffitt

1993. A user study comparing head-mounted and stationary displays. In *Virtual Reality, 1993. Proceedings., IEEE 1993 Symposium on Research Frontiers in*, Pp. 41–45. IEEE.

Pausch, R., J. Snoddy, R. Taylor, S. Watson, and E. Haseltine

1996. Disney's aladdin: first steps toward storytelling in virtual reality. In *Proceedings* *of the 23rd annual conference on Computer graphics and interactive techniques*, Pp. 193–203. ACM.

Piekarski, W. and R. Smith

2006. Robust gloves for 3d interaction in mobile outdoor ar environments. In *Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality*, Pp. 251–252. IEEE Computer Society.

Ponto, K., J. Kohlmann, and R. Tredinnick

2015. Dscvr: designing a commodity hybrid virtual reality system. *Virtual Reality*, 19(1):57–70.

Pratt, D. R., P. T. Barham, J. Locke, M. J. Zyda, B. Eastman, T. Moore, K. Biggers, R. Douglass, S. Jacobsen, M. Hollick, et al.

1994. Insertion of an articulated human into a networked virtual environment. In *AI, Simulation, and Planning in High Autonomy Systems, 1994. Distributed Interactive Simulation Environments., Proceedings of the Fifth Annual Conference on*, Pp. 84–90. IEEE.

RaspberryPi

2013. `https://raspberrypi.org/`.

Razzaque, S., Z. Kohn, and M. C. Whitton

2001. Redirected walking. In *Proceedings of EUROGRAPHICS*, volume 9, Pp. 105–106. Citeseer.

Ruddle, R. A., S. J. Payne, and D. M. Jones

1999. Navigating large-scale virtual environments: what differences occur between helmet-mounted and desk-top displays? *Presence: Teleoperators & Virtual Environments*, 8(2):157–168.

Sebok, A., E. Nystad, and S. Helgar

2004. Navigation in desktop virtual environments: an evaluation and recommendations for supporting usability. *Virtual Reality*, 8(1):26–40.

Sherman, W. R. and A. B. Craig

2002. *Understanding virtual reality: Interface, application, and design.* Elsevier.

Slater, M.

2003. A note on presence terminology. *Presence connect*, 3(3):1–5.

Smith, S. P. and S. Du'Mont

2009. Measuring the effect of gaming experience on virtual environment navigation tasks. In *3D User Interfaces, 2009. 3DUI 2009. IEEE Symposium on*, Pp. 3–10. IEEE.

Spiers, H. J. and E. A. Maguire

2006. Thoughts, behaviour, and brain dynamics during navigation in the real world. *NeuroImage*, 31(4):1826 – 1840.

Steed, A. and S. Julier

2013. Design and implementation of an immersive virtual reality system based on a smartphone platform. In *3D User Interfaces (3DUI), 2013 IEEE Symposium on*, Pp. 43–46. IEEE.

Steinicke, F., G. Bruder, K. Hinrichs, A. Steed, and A. L. Gerlach

2009. Does a gradual transition to the virtual world increase presence? In *Virtual Reality Conference, 2009. VR 2009. IEEE*, Pp. 203–210. IEEE.

Suma, E., S. Finkelstein, M. Reid, S. Babu, A. Ulinski, and L. F. Hodges

2010a. Evaluation of the cognitive effects of travel technique in complex real and virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 16(4):690–702.

Suma, E. A., S. L. Finkelstein, S. Clark, P. Goolkasian, and L. F. Hodges

2010b. Effects of travel technique and gender on a divided attention task in a virtual environment. In *3D User Interfaces (3DUI), 2010 IEEE Symposium on*, Pp. 27–34. IEEE.

Suma, E. A., B. Lange, A. S. Rizzo, D. M. Krum, and M. Bolas

2011. Faast: The flexible action and articulated skeleton toolkit. In *Virtual Reality Conference (VR), 2011 IEEE*, Pp. 247–248. IEEE.

Sutcliffe, A. G. and K. K. Deol

2000. Evaluating the usability of virtual reality user interfaces. *Behaviour & IT*, 19(6):415–426.

Sutherland, I. E.

1963. *Sketchpad, A Man-Machine Graphical Communication System*, Outstanding Dissertations in the Computer Sciences. Garland Publishing, New York.

Sutherland, I. E.

1965. The ultimate display. *Multimedia: From Wagner to virtual reality*, Pp. 506–508.

Sutherland, I. E.

1968. A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I*, AFIPS '68 (Fall, part I), Pp. 757–764, New York, NY, USA. ACM.

Thomas, J., R. Bashyal, S. Goldstein, and E. Suma

2014a. Muvr: A multi-user virtual reality platform. In *Virtual Reality (VR), 2014 iEEE*, Pp. 115–116. IEEE.

Thomas, J., R. Bashyal, S. Goldstein, and E. A. Suma

2014b. Muvr: A multi-user virtual reality platform. In *2014 IEEE Virtual Reality, VR 2014, Minneapolis, MN, USA, March 29 - April 2, 2014*, Pp. 115–116.

Usoh, M., E. Catena, S. Arman, and M. Slater

2000. Using presence questionnaires in reality. *Presence: Teleoperators & Virtual Environments*, 9(5):497–503.

VRGeeks

2012. An hmd in a ski mask? `http://cb.nowan.net/blog/2011/04/16/an-hmd-in-a-ski-mask/`.

Vuzix

2007. iwear vr 920 headset. `https://arstechnica.com/gadgets/2007/11/virtual-reality-headset-review/`.

Watsen, K., R. Darken, and M. Capps

1999. A handheld computer as an interaction device to a virtual environment. In *Proceedings of the third immersive projection technology workshop*.

Weiser, M.

1994. Creating the invisible interface:(invited talk). In *Proceedings of the 7th annual ACM symposium on User interface software and technology*, P. 1. ACM.

Werkhoven, P., J. B. van Erp, and T. G. Philippi

2014. Navigating virtual mazes: The benefits of audiovisual landmarks. *Displays*, 35(3):110 – 117.

Wilson, J. R.

1999. Virtual environments applications and applied ergonomics. *Applied Ergonomics*, 30(1):3–9.

Wingrave, C. A., B. Williamson, P. D. Varcholik, J. Rose, A. Miller, E. Charbonneau, J. Bott, and J. J. LaViola Jr

2010. The wiimote and beyond: Spatially convenient devices for 3d user interfaces. *IEEE Computer Graphics and Applications*, 30(2):71–85.

Zanbaka, C. A., B. C. Lok, S. V. Babu, A. C. Ulinski, and L. F. Hodges

2005. Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. *IEEE Transactions on Visualization and Computer Graphics*, 11(6):694–705.