IMPLEMENTATION AND ANALYSIS OF CO-LOCATED VIRTUAL REALITY FOR COLLABORATIVE SCIENTIFIC DATA VISUALIZATION

by

Jordan McGraw

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. David Whittinghill, Chair
Polytechnic Institute

Mr. George Takahashi
Purdue Research Computing

Dr. Danny Milisavljevic
Department of Physics and Astronomy

Dr. Tim McGraw
Polytechnic Institute

Approved by:
Dr. Nicoletta Adamo

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DEFINITIONS

Active Stereo: A 3D rendering technique wherein "computers generate perspective views that are … in synchrony with electronic shutter glasses [worn by the primary participant]. The active eyewear is [made] transparent in front of the left eye when the left eye image is projected, and opaque otherwise; similarly, the right eye receives the [image rendered for the] right [eye]" (Defanti et al., 2010. p. 17).

Aura: "A region [in] which a user desires interaction; this can be set for different mediums (such as audio, graphics etc)" (Joslin, Thalmann, & Giacomo, 2004, p. 5).

Avatar: Unlike "autonomous software agents", avatars are "embodiments behind which [there] are users in 'live' interaction" (Churchill & Snowdon, 1998, p. 9).

CAVE: A "Cave Automatic Virtual Environment" (Defanti, 1996, p. 43) is an immersive, projection-based, cube shaped, walk-in virtual reality system consisting of four to six walls wherein participants wear stereo glasses to interact with 3D computer-generated content (Defanti, 2010, p. 17).

Client-Side: Regarding computer networking, "the action takes place on the user's (the client's) computer" (Morris, 2018).

Collaboration: Intuitively described as a situation wherein "peers are more or less at the same level, can perform the same actions, have a common goal and work together" (Dillenbourg, 2007, p. 7).

Computer-Supported Collaborative Learning: A branch of the learning sciences concerned with studying how people can learn together with the help of computers (Stahl, Koschmann, & Suthers, 2006, p. 1).

Co-Location: That which permits "two or more users to effectively share a common virtual environment as well as a real place, and to interact and to engage each other directly" (Simon, 2005, p. 24).

Collaborative Virtual Environment (CVE): "A distributed, virtual reality that is designed to support collaborative activities … within which multiple users can interact with each other and with simple or complex data representations" (Churchill & Snowdon, 1998, p. 3).

Cyberspace: "Text-based networked VR" as opposed to "visually immersive VR" (Psotka, 1995, p. 406).

Engagement: A dimension which stems from "challenge, interactivity, realism, fantasy, cooperation, and immersion" (Psotka, 1995, p. 409).

Focus: “A sub-region that defines the actual focal point of a user; this could be considered in some respects as the view frustum of the user, but can be controlled on a more social level” (Joslin, Thalmann, Giacomo, 2004, p. 5).

Haptic Feedback: A tactile “response in form of vibration [or pressure]” (Edwards, Bielawski, Prada, & Cheok, 2018, p. 5).

Head Mounted Display (HMD): “HMDs consist of two LCD screens mounted in a glasses-like device and fixed relative to the wearer’s eye position, and portray the virtual world by obtaining the user’s head orientation (and position in some cases) from a tracking system” (Sousa Santos, 2008, p. 164).

Immersion: Slater (2003) choses to use “the term 'immersion' to stand simply for what the technology delivers from an objective point of view. The more that a system delivers displays (in all sensory modalities) and tracking that preserves fidelity in relation to their equivalent real-world sensory modalities, the more that it is 'immersive'. This is something that can be objectively assessed, and relates to different issues than how it is perceived by humans” (Slater, 2003, p. 1).

Nimbus: “The region in which a user wishes be made themselves known; a smaller nimbus can be considered as a low desire to interact, whereas a large nimbus indicates a high interaction desire” (Joslin, Thalmann, & Giacomo, 2004, p. 5).

Novelty: “The thrill of new technologies”. Stated that “the engagement and excitement that is part of the VR phenomenon is an obvious candidate for exploitation in education and training” (Psotka, 1995, p. 409).

Presence: Described as “a human reaction to immersion” (Slater, 2003, p. 2). “Presence is about form, the extent to which the unification of simulated sensory data and perceptual processing produces a coherent 'place' that you are 'in' and in which there may be the potential for you to act” (p. 2).

Sandbox: “An area of play in which the user has no set objective and is free to do as he wishes in the confines of the playing area” (Learmouth, 2015).

Simulation: High engagement computer-mediated experiences which “allow the learner to observe cause and effect, and learning is therefore experience-based” (Leder, et. al, 2019, p. 285).

Vection: Sometimes described in the context of looking out a vehicle window, it is “the feeling of self movement when a large field display is moved with respect to an observer. Thus people placed in the center of a drum which rotates independent of them will, under the right circumstances, feel that it is they who are rotating, not the drum.” (Ware, Arthur, & Booth, 1997, p. 39).

Virtual Reality (VR): “VR can be described as a mosaic of technologies that support the creation of synthetic, highly interactive three dimensional (3D) spatial environments that represent real or non-real situations” (Mikropoulos & Natsis, 2011, p. 769).

Virtual Worlds: Described as “persistent virtual environments in which people experience others as being there with them - and where they can interact with them” (Schroeder, 2008, p. 2).

Virtual Environment (VE): Described as “a computer-generated display that allows or compels the user (or users) to have a sense of being present in an environment other than the one they are actually in, and to interact with that environment” (Schroeder, 2008, p. 2).

WYSIWIS: Acronym standing for “What You See Is What I See” (Park, Kapoor, & Leigh, 2000, p. 73). “Strict-WYSIWIS is a mode of operation whereby all the users see and share the same information and interface” (p. 74).

LIST OF ABBREVIATIONS

(2D) Two-Dimensional

(3D) Three-Dimensional

(API) Application Programming Interface

(AR) Augmented Reality

(CAVE) Cave Automatic Virtual Environment

(CSCL) Computer Supported Collaborative Learning

(CVE) Collaborative Virtual Environment

(DOF) Degrees of Freedom

(EVE) Educational Virtual Environment

(HMD) Head Mounted Display

(LAN) Local Area Network

(LIDAR) Light Detection and Ranging

(PC) Personal Computer

(SDK) Software Development Kit

(UI) User Interface

(UX) User Experience

(VE) Virtual Environment

(VR) Virtual Reality

(WYSIWIS) What You See Is What I See

ABSTRACT

Advancements in virtual reality (VR) technologies have led to overwhelming critique and acclaim in recent years. Academic researchers have already begun to take advantage of these immersive technologies across all manner of settings. Using immersive technologies, educators are able to more easily interpret complex information with students and colleagues. Despite the advantages these technologies bring, some drawbacks remain. One drawback is the difficulty of engaging in immersive environments with others in a shared physical space (i.e., with a shared virtual environment). A common strategy for improving collaborative data exploration has been to use technological substitutions to make distant users feel they are collaborating in the same space. This research, however, is focused on how virtual reality can be used to build upon real-world interactions which take place in the same physical space (i.e., collaborative, co-located, multi-user virtual reality).

In this study we address two primary dimensions of collaborative data visualization and analysis as follows: [1] we detail the implementation of a novel co-located VR hardware and software system, [2] we conduct a formal user experience study of the novel system using the NASA Task Load Index (Hart, 1986) and introduce the Modified User Experience Inventory, a new user study inventory based upon the Unified User Experience Inventory, (Tcha-Tokey, Christmann, Loup-Escande, Richir, 2016) to empirically observe the dependent measures of Workload, Presence, Engagement, Consequence, and Immersion. A total of 77 participants volunteered to join a demonstration of this technology at Purdue University. In groups ranging from two to four, participants shared a co-located virtual environment built to visualize point cloud models of exploded supernovae. This study is not experimental but observational. We

found there to be moderately high levels of user experience and moderate levels of workload demand in our results. We describe the implementation of the software platform and present user reactions to the technology that was created. These are described in detail within this manuscript.

CHAPTER 1. **INTRODUCTION**

1.1 Introduction

This research is focused on the software architecture and user experience of participants using a novel collaborative virtual reality application. We elected scientific data exploration as the activity of choice by virtue of accessibility to academic resources and expertise. Participants used this technology to engage with complex astronomical datasets in order for the research team to observe the impacts of virtual collaboration. The exploration of this technology is intended to provide subsequent VR researchers with insight into the development of this collaborative modality.

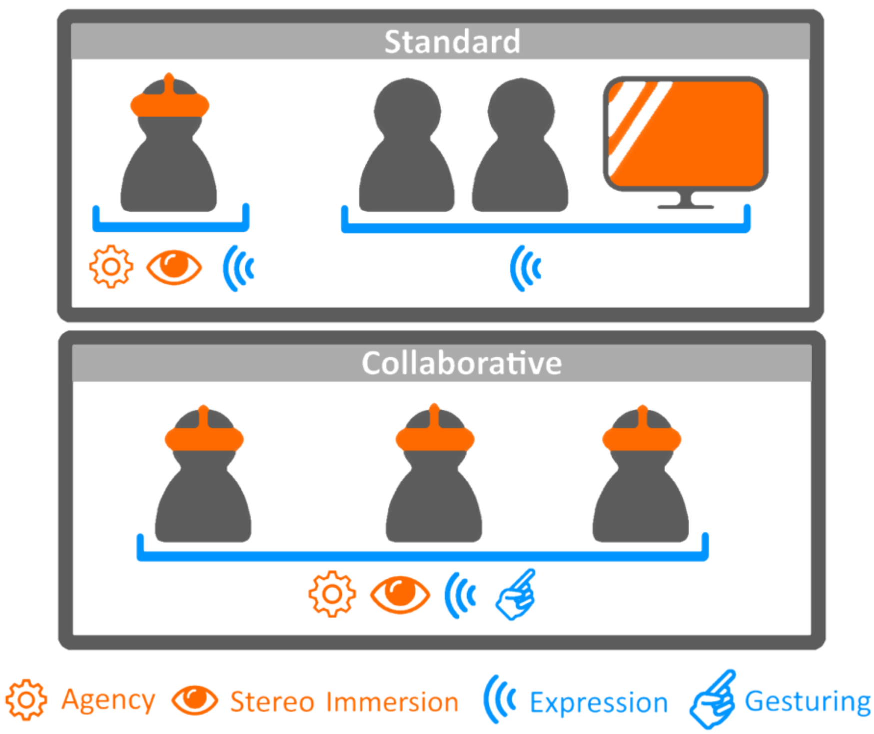


Figure 1.1 Benefits afforded to participants in VR and their passive observers.

Figure 1.1 illustrates the basic intuition of this research. The comparison demonstrates that a traditional virtual reality (VR) user has full agency and high throughput for spatial information in the virtual environment (VE), however their communication towards outside observers is limited by the nature of their device. The passive observers viewing a standard monitor display are not granted any of the perceptual advantages of VR and are limited in their communication with the active VR participant (e.g., body language, pointing, and gesturing). The comparison shows our implemented method of using co-located collaborative VR. When implemented impaired dimensions approach maximization- both groups perceive a synchronous virtual environment and the throughput for communication is greatly improved.

1.2 Problem Statement

Current immersive technologies produce isolated viewing experiences which limit the throughput of natural communication techniques relied upon for effectively relating complex spatial information between individuals. Existing collaborative displays suffer from distorted perspectives or limited agency, whereas personal immersive displays lack convergence between virtual and physical space.

1.3 Research Questions

1. What are the steps necessary for building a lightweight, co-located virtual environment for visualizing spatial astronomical data?
2. What are the perceptions of workload, engagement, immersion, presence and overall user experience among university-level individuals using the co-located virtual environment to explore 3D astronomical data?

1.4 Hypothesis

The primary hypothesis supposes the co-located virtual environment may be created using modern consumer-grade virtual reality devices and APIs.

The secondary hypothesis supposes the novel co-located virtual reality technology provides measurable levels of workload and user experience dimensions.

1.5 Scope

Individuals within the Purdue University community were the sample for data collection. The participants were limited to individuals who were students or visiting faculty at the university. Our non-probabilistic choice of sampling was aimed to inform the researchers on specific information, mainly that which is concerned with the quality of user experience among participants in higher level education. Survey instruments measured the expressed perceptions of the participants. Testing sessions occurred once, for the duration of one hour, and included a set of Likert-type questionnaires. Given the potential for discomfort, participants were allowed to opt out of the experiment at any time but would not serve as a data point for statistical analysis.

1.6 Significance

Due to the present limitations in collaborative VR experiences, the variety of modern applications is limited. By overcoming these limitations, the applicability and ubiquity will increase, thus enabling greater engagement and presence for a larger number of users in virtual reality. The field of scientific data visualization benefits from an understanding of the technologies which contribute to its findings. If the acceleration of this technology remains parallel to recent years, additional research will be needed.

1.7 Assumptions

It was assumed that individuals would be capable of using the virtual reality device to the satisfaction of the research requirements and that participants would provide their responses honestly and attentively. This research assumed higher throughput for communication was preferable when sharing spatial scientific data. It was assumed that the inability for multiple users to physically occupy the same virtual environment is what leads to inferior communicative throughput. It was also assumed that participants in the study would provide information to the best of their knowledge, and that data collection tools provided accurate and consistent measures across trials.

It was assumed that when extracting a subset of the Unified User Experience Questionnaire (Tcha-Tokey et al., 2016) to create the Modified User Experience Questionnaire that the original inventory's validity and reliability would not be adversely affected if its combined length were altered.

1.8 Limitations

Participants were required to engage with novel devices which occasionally induce discomfort. Discomfort, such as nausea or eyestrain, should be avoided for ethical and practical reasons (as to avoid collecting skewed or misleading data). The research team attempted to minimize the potential for simulator sickness and monitored indications of physical discomfort while testing.

There may be restrictions by the limits of self-report surveys, participant drop-out, sample size, and absence of retesting. Though experimental, the findings may not sufficiently permit causal conclusions to be drawn and will therefore be correlational and observational.

1.8.1 Disruptions

Interruptions in network communications during testing, such as unanticipated power loss or server failure, would likely result in an undesirable, non-continuous experience. For this reason, network latency was monitored throughout each trial session. Severe disruptions in connectivity would cease the testing session and any subsequent data would be marked as void. Physical interruptions from outside the virtual environment, such as evacuations, phone calls, unexpected visitors, or disruptive noises, odors, etc., were expected to diminish the continuity of testing. Adequate signage and instructions remedied the potential for physical disruptions.

1.8.2 Recourse

Interruptions during testing would be detailed for discussion in the final analysis. If deemed severe enough, the trial would be omitted from statistical analysis and would be accompanied by clear reasoning for the recourse.

1.9 Delimitations

This research is intended to utilize a subset of potential hardware devices and software solutions available to our laboratory. We elected to transmit network data over a local area network (LAN) to reduce the latency between devices. Testing occurred in a large VR showroom free of any props or furniture for the safety of our participants.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Introduction

Linder, Miloff, Hamilton et al. (2017) note that "HMDs used to be inaccessible and expensive (often costing more than 10,000 USD), needed to be paired with equally expensive high-end computers, and required a high degree of technological expertise to install and operate" (p. 405). Improvements have emerged with mobile virtual reality platforms, which integrate all the necessary hardware components onto the same device. Mobile virtual reality platforms have the advantage of being "portable and relatively inexpensive" (p. 407), however, "contemporary limitations include lower computational power, limited types of user-input (including [the] types of head movements that can be registered), and no convenient way to share the virtual experience" (Linder, Miloff, Hamilton et al., 2017, p. 407).

As it pertains to this evaluation, virtual reality is primarily a visuomotor experience in which presence and immersion are key (Slater, 2003). This is different from what may otherwise be described more generally as "cyberspace". Cyberspace is characterized as a variant of virtual reality which is primarily text-based and networked (Psotka, 1995, p. 406). Since virtual realities are dependent on context, this distinction is pragmatic. For the purpose of this research, virtual reality is defined as that which surrounds the user with a virtual environment imbued with perceived physicality and a visual perspective- both of which are not attributed to cyberspace. As Mikropoulos and Natsis write in their extensive review of Educational Virtual Environments (EVEs), "VR can be described as a mosaic of technologies that support the creation of synthetic, highly interactive three dimensional (3D) spatial environments that represent real or non-real situations" (2011, p. 769).

2.2 Virtual Reality Applied to Computer-Supported Collaborative Learning

There are many key topics in proximity to virtual reality. These topics include the usage of head mounted displays (HMDs), tracking solutions, gesture recognition, force feedback (haptics), and stereo sound (Psotka, 1995).

This technology is of significant interest for many in the field of education and training. Though sometimes idealized, academic literature does not shy away from projecting narratives of what this technology would provide to the user of the future. In one such narrative, a junior high student is followed in her fantastic and exciting tour of anatomical systems, molecular chemistry, and orbital dynamics. Throughout the narrative, she is led by her teacher towards uncovering insights of her own. Alongside her are her peers and fellow students, with whom she can observe and interact. The author of the narrative is eager to place her amazement and intellectual curiosity in view of the reader. This narrative summarizes directly and indirectly many of the aspirations educators hold for their classrooms. It addresses directly the desire to concretize abstract topics of science in ways which are engaging and digestible for students. Orbital dynamics, molecular chemistry, and anatomical systems share an element of cognitive abstraction which must be effectively precipitated from the instructor onto the students. Indirectly, it gives nods to the important influence of a shared experience between students in virtual reality (Psotka, p. 421-422).

Paradoxically, collaborative learning is still about individual learning (Westera, 1999). The outcome of collaborative learning may only be evaluated by the performance of individual subjects. Despite efforts to coordinate and develop shared knowledge through cooperation, "learning remains a strictly individual process, actually located in the brain of the person involved" (Westera, 1999, p. 20). Under these conditions, it is better said that collaborative learning is focused moreover on optimizing the conditions under which the student engages with the educational material. Educators would be keen to recognize the applicability of the old adage, "You can lead a horse to water, but you cannot make it drink". In the narrative put forth by Psotka (1995), the presence of her instructor is primarily detailed from an oblique perspective where from the majority of her insights are discovered through individual exploration. This is undoubtedly a persistent challenge to the introduction of virtual reality in the classroom. Educators should be cognizant of virtual reality's inability to insulate their content from educational shortcomings more broadly. The literature recognizes the perceived inadequacy of a one-size fits all approach to activities in the classroom, virtual or otherwise. This is the area of inquiry for nearby researchers in the field of Computer-Supported Collaborative Learning.

Computer-Supported Collaborative Learning (CSCL) is a discipline concerned with the educational merits of computer mediated learning environments.

> The goal for design in CSCL is to create artifacts, activities and environments that enhance the practices of group meaning making. Rapid advances in computer and communication technologies in recent decades, like the Internet, have dramatically changed the ways in which we work, play, and learn. (Stahl, Koschmann, & Suthers, 2006, p. 9)

CSCL gained popularity in response to the rise of educational software in the 1990's which promoted individualistic and "isolated" approaches to learning (Stahl, Koschmann, & Suthers, 2006, p. 1). With the introduction of wider and more available internet resources, CSCL found increased applicability within various domains. Within the field, collaboration is viewed as "a process of shared meaning construction" (Stahl, Koschmann, & Suthers, 2006, p. 8). Meaning derived from collaborative experiences are highly contextualized by collective, internal, and self-referential remarks (i.e., the centrality of the learning experience is distributed across participants and over time simultaneously). Therefore, meaning cannot be localized to any individual utterance or moment in time; similar to how a word is contextualized by the containing sentence, and the sentence by the containing paragraph, and so forth.

The construction of meaning is described not, therefore, as a mental process as much as an "interactional achievement" (Stahl, Koschmann, & Suthers, 2006). This notion merits the attention of the paradox described above, in which any learning that takes place must ultimately occur on an individual level. According to Stahl et al. (2006), "Collaborative learning involves individual learning, but is not reducible to it" (p. 3). This tension of group versus individual learning is further recognized by Stahl and his colleagues to be at the heart of CSCL.

Further research has lent continued investigation into what should be meant by the term "collaboration". Four descriptions are raised by Pierre Dillenbourg (2007) in his paper "What Do You Mean By 'Collaborative Learning'?". According to Dillenbourg, collaboration can be characterized as situational, interactive, mechanistic, and effective (p. 7). Special emphasis is placed upon the fourth element to denote the difficulty of consolidating a unified approach to measurement among CSCL researchers.

2.3 Educational and Instructional Usage of Modern Virtual Reality

At George Mason University, Dede et al. (1997) describe their research of virtual reality as based upon the expansion of cyberspace and its direct competition for our attention. They emphasize the importance of evaluating the strengths and limits of virtual reality before it becomes "ubiquitous in the form of video games" (p. 2). Irrespective of whether such a footrace is necessary, it has become clear that their estimation of virtual reality's utility and research necessity is well established. One of their investigations placed student learners, aged around late high school, in a physics simulation aimed to "remediate misconceptions about electric fields, electric potential, and Gauss's law" (p. 15). In their evaluation of learning outcomes, Dede notes that students demonstrated a statistically significant improvement in their understanding of the subject (as measured from by their pretest-posttest design) from both 2D and 3D VR versions of the material. Understandably, however, students who participated in the 3D version were better able to describe electrostatic fields in 3D than their peers using the 2D simulation, all but one of whom limited their descriptions to a single plane. In addition, they measured factors of simulator sickness and motivation, neither of which significantly predicted learning outcomes in the VR learners. Despite usability challenges and simulator sickness, participants who engaged with the 3D representations were described to have learned more effectively than those within the 2D alternative. Dede (1997) notes that subjective ratings attributed improved learning to the "representational capabilities virtual reality enables" (p. 18).

Virtual reality is acknowledged within the sphere of CSCL to hold many potential avenues of further investigations. In 1999, William Winn and Randy Jackson of University of Washington put forth fourteen propositions through which they speculated the various utilities of virtual reality for educational use. As noted in the literature broadly, cost and safety concerns are often primary reasons for implementing virtual reality. Additionally, computer simulations yield the advantage of an inherent ability to fine-tune scenarios which might otherwise be difficult or impossible to coordinate. Simulations of this nature can be observed in the psychological literature addressing exposure therapy for patients with aerophobia, the fear of flying. Consistent access to resources or ideal therapeutic environments may be costly or unpredictable. In a study performed by Triscari et al. (2015), Cognitive Behavioral Therapy in combination with virtual reality was demonstrated to be "as efficient as traditional cognitive behavioral treatments integrated with systematic desensitization" for the treatment of aerophobia. Within the domain of disaster response, researchers were led to investigate the performance of US Navy medical providers in a training simulation intended to teach "cognitive assessment and treatment skills" (Freeman et al., 2001). In such cases, predictable and configurable scenarios are key elements to effective treatment and training.

Reification and transduction are two essential components to Winn and Jackson's (1999) investigation of virtual environments (VE). Both terms relate to the concretization of abstract phenomena which may have no physical form. Transducers are devices which bring extra-sensory information into the scope of human interpretation. One such example details the usage of sonar to chart ocean floor topology. Though neither the ocean floor depth nor the sonic pulses used to map the underwater terrain are detectable by human senses, we construct visual representations from the data to serve as our models. Reification describes the processes by which metaphors and analogies are used to represent phenomena without natural form. Many abstract linguistic categories rely on reification for them to be properly understood. Scientific concepts such as atomic radii are reified through appealing to sphere models whose radii are evident to see.

In an evaluation of their research, Dede et al. (1997) cite a learner-centered approach as yielding the most insight into the educational capabilities of virtual reality. They describe this as an approach that "focuses simultaneously on the learning experience, the learning process, and learning objectives" (p 32). Their evaluation stresses a requirement to understand the relationship between the needs of the learner and the capabilities and limitations of the technology in question. This concern is apt for any researcher investigating the utility of a technology which is largely not well-understood by those who would like to implement it. In addition, they claim lessons may be more effective when spread across the course of several sessions. They attribute this to the fatigue and cognitive overhead of synthesizing new information while simultaneously mastering the interfaces of a new technology. One interesting topic raised in their evaluation points towards the incompatibility of many 2D oriented designs in 3D contexts. They note that traditional interfaces (such as planar graphical user interfaces) could not be simply lifted into a 3D context without needing to reevaluate their designs. "Standard approaches to building 2-D microworlds … do not scale well to 3-D worlds. Multimodal interaction and multisensory communication are important parts of an immersive experience. The development of VR interface tools that facilitate these interactions is a much-needed advance." (p. 33).

Poor practical consideration often lies beneath ill-conceived projects which attempt to exalt virtual reality beyond its region of serviceability. For those who fail to distinguish virtual reality from traditional simulation, the point is often lost. Winn and Jackson tacitly bemoan an interaction with a biology teacher who described "how wonderful it would be to create a virtual biology lab, with virtual microscopes that students could peer through to study virtual creatures swimming around in a drop of water." The researchers follow in stating "We believe that the teacher has missed the point" (1999, p. 8).

2.4 Co-Located Multi-User Virtual Reality

Modern HMD-based virtual reality precludes the involvement of spectators. Those who are not actively interfacing with the virtual reality device are limited at best to a mirrored projection of what the active user is seeing from their perspective. This may provide utility where scenario monitoring is necessary, such as in exposure therapy sessions where a participant's view in virtual reality is "mirrored on an ordinary display that a clinician in the same room may use to direct the exposure context" (Lindner, Miloff, Hamilton et al., 2017, p. 407). However, as Lobser (2017) and colleagues note, "virtual reality is typically a solitary experience. One person sits alone with their headset on while everyone else watches them" (p. 1). At SIGGRAPH 2017, they demonstrated the use of multiple HTC Vives for a "location-based, multi-user" experience in which users jointly roleplayed as birds in a colorful sandbox environment (Lobser, 2017, p. 1).

Co-located virtual reality for training and scientific visualization is not entirely new. The CAVE, a room-sized projection-based VR booth created by the Electronic Visualization Laboratory in 1991 (Defanti, 2011, p. 17) is a "walk-in virtual reality environment" (p. 16) wherein "all participants wear active stereo glasses to see and interact with complex 3D objects." (p. 17). In addition, "one participant wears an ... orientation sensor ... so that when he/she moves within the CAVE, correct viewer-centered perspective and surround stereo projections are produced quickly enough to give a strong sense of 3D visual immersion." (p. 17). Unlike fully immersive HMDs, "CAVE participants see projected computer-generated stereo scenes but can also see their arms and bodies and can easily interact with one another." (p. 17). The nature of the system presents various costs and limitations. "A CAVE with three walls and a floor minimally requires a 13m-by-10m space with a 4.5m high ceiling." (p. 17). They "require significant ... space, projectors costing $5,000-$500,000 [per] screen, projector maintenance/alignment, lamp replacement, significant power and cooling, specialized screen material and controlled lighting conditions, all of which severely limit their acceptance and adoption in everyday workspaces, public venues, and homes." (p. 17). Despite implementation and maintenance challenges, CAVE systems have seen high utility among data scientists and simulation researchers.

Co-located data visualization has been performed on head-mounted displays using Augmented Reality (AR). Augmented Reality "is often used to refer to interfaces in which two and three-dimensional computer graphics are superimposed over real objects, typically viewed through head-mounted or handheld displays" (Billinghurst, Kato, 2002, p. 1). The primary element of distinction between AR and VR lies in the superimposition of graphics onto the real world (as is the case with AR and not with VR). VR intends to occlude the entire world with a virtual environment, whereas AR does not— AR aims to overlay information onto the real world. Billinghurst and Kato propose five key features (p. 4) pertinent to collaborative AR; Virtuality (objects do not exist physically), Augmentation (real objects may be annotated virtually), Cooperation (users may cooperate naturally), Independence (users control their perspective), and Individuality (data can be tailored to each user). These describe the dimensions upon which they identified value in collaborative augmented reality sessions.

Further work has explored the usage of a non-HMD user sharing in the experience of an active user in VR (Gugenheimer et al., 2017). This style of interaction is described as an "asymmetric" solution (p. 5). Their research was primarily focused on enhancing the interaction between HMD and non-HMD users. Gugenheimer et al. (2017) account that "in the VR context, co-located settings are difficult to provide as usually only one VR HMD is available and only one player can wear it at a time. However, there are a few co-located VR games that make use of other means to circumvent this limitation" (p. 4). They further enumerate several games which implement asymmetric interaction and note that they are generally well received. They claim their proof-of-concept prototype, ShareVR, is "the first VR system enabling physical gaming experiences between HMD and Non-HMD users." (p. 4). They concluded from their research that it provided an "advantage in terms of enjoyment, presence and social interaction" as measured through their user studies (Gugenheimer et al., 2017, p. 11).

CHAPTER 3. METHODOLOGY

3.1 Introduction

The aim of this project was to evaluate the user experience of participants visualizing volumetric datasets in real-time, co-located, multi-user virtual reality.

3.2 Technological Specifications

3.2.1 Software and Hardware Deployment

The collaborative data visualization platform was built in-house and custom tailored to deliver a specialized experience of virtual collaboration for user testing. The simulation software was built using Unity version 2017.4.28f1 and deployed for testing on multiple Oculus Quests running Android OS in developer mode. To achieve synchronization across the simulation, the application was locally networked over WiFi using the Lidgren networking library. Lidgren uses "a single UDP socket to deliver a simple API for connecting a client to a server, reading, and sending messages" (Lidgren, 2015). The application was built as an .apk file from Unity and installed on the Oculus Quests using a custom script executing a sequence of Android Debug Bridge (ADB) build commands.

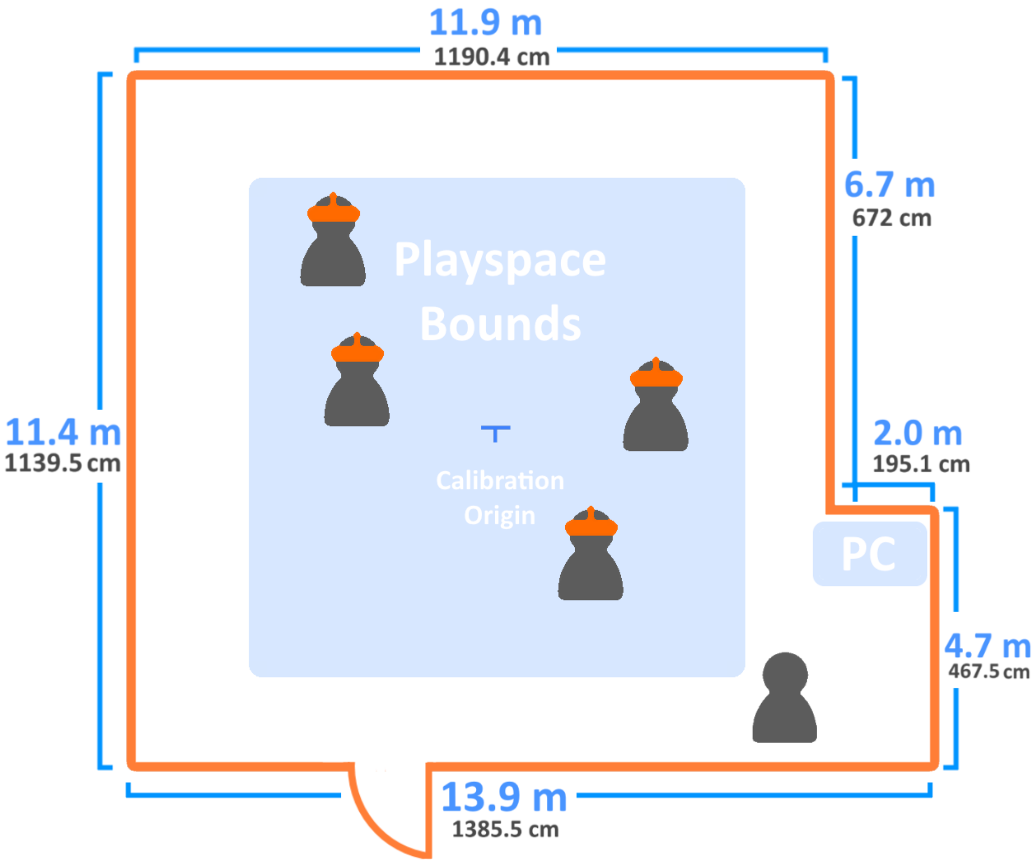


Figure 3.1 Diagram of the testing environment (~135.65 sq. meters)

Testing occurred in a laboratory facility which had previously been used to house a CAVE theater system. The VR playspaces were calibrated to their maximum scale from the center-mark of a floorspace approximately equal to 135.65 sq. meters (1139.5 cm by 1190.4 cm) (Bannister, 2019). Calibrating each Oculus Quest headset to the same point in the room ensured that all users shared the same physical mapping of the virtual environment. Mobile battery packs were available as emergency backups for low-power headsets. Due to the duration and frequency of testing, it was imperative to monitor device power and charge headsets regularly.

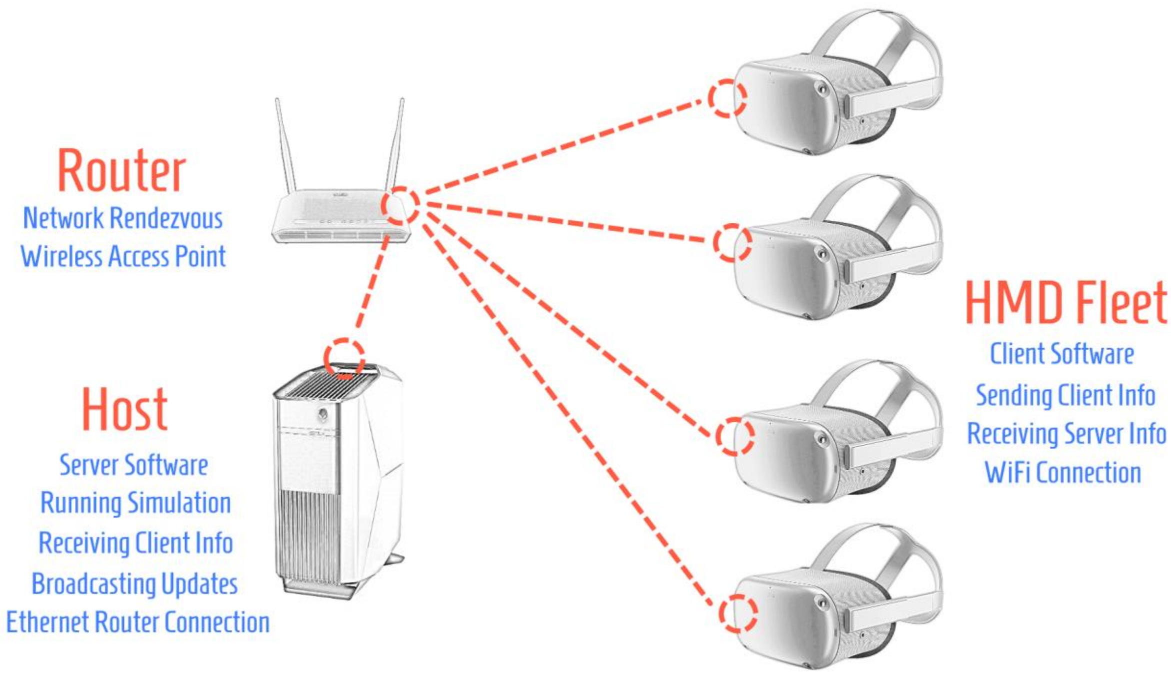


Figure 3.2 Diagram of network connections between devices

3.2.2 Datasets

Participants were presented with datasets depicting astronomical measurements, specifically supernova events. These datasets were coded with the following names; N132D (Law, Milisavljevic, et al., 2020), E0102 (Milisavljevic et al., 2020), Cassiopeia A (Milisavljevic & Fesen, 2013, 2015), and Crab (Martin, Laurent, & Milisavljevic, 2020). These datasets were selected for their availability, variety of features, and levels of complexity. Each dataset was represented using point-cloud rendering.

3.2.3 File Importing

Input data files for this application were formatted as plain-text, comma-separated values or XYZ entries. Data entries were parsed upon request from the dataset and partitioned using simple delimiters. Files were read locally from disk or fetched via web address. As files are parsed, metadata of the volume bounds and center of mass are calculated and stored for visualizations. To groom the data in advance (as the scale of each individual dataset can vary by orders of magnitude) each datapoint was further normalized within the [0,1] range. To remove sampling bias for point clouds optimization, we stored an additional version of the data whose entries were shuffled randomly.

3.2.4 Isosurface Modeling Algorithms

Within the application datasets can be visualized interchangeably with GPU-instanced particle models and procedurally generated isosurface meshes.

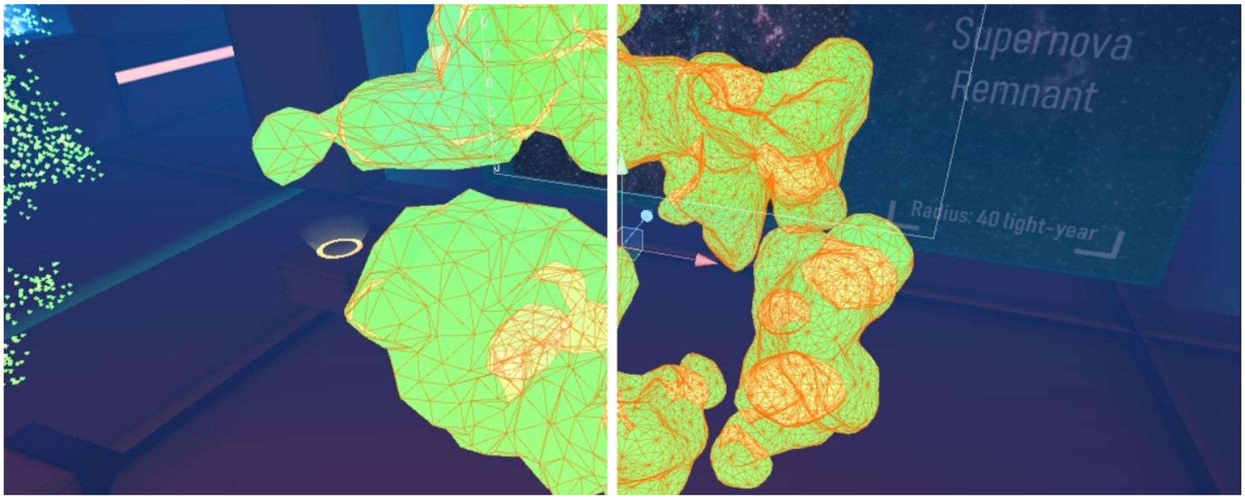


Figure 3.3 (Before and after) Shaded wireframe view of the Catmull-Clark smoothing algorithm applied to an N132D isosurface model

These isosurface models were created using an implementation of the Marching Cubes algorithm and later retopologized using the Catmull-Clark smoothing algorithm.

For this application, the use of Catmull-Clark was suitable for refining isosurfaces used to display general bounding volumes. However, it is worth acknowledging its classification as an approximation subdivision refinement scheme and not an interpolative refinement scheme (Zorin, 2000). Hence, this smoothing algorithm may not be suitable in other applications for which it is critical to preserve the isovalues of the original model.

3.2.5 Optimizing Point Cloud Rendering

Each supernova dataset contained many thousands of points. We achieved stable rendering for multimillion-point particle systems in VR using indirect rendering optimizations on an HTC Vive, however these optimizations were not supported for the Oculus Quest's OpenGL ES specification during development.

Point cloud models were programmed to display a subsample of their total number of points to optimize GPU resources while viewing multiple datasets simultaneously. They were further subsampled by a percentage factor of their current scale. Hence, a point cloud model scaled to half its original size would result in the representation displaying only half its number of points.

GPU rendering resources were shared among datasets, therefore scaling models provided a simple way to “minimize” a representation when not in use.

Point cloud models could be provided with an optional noise vector upon which to feather the points in case the original measurement instrument introduces biased or stratified sampling.

3.2.6 Aesthetics of the Virtual Environment

The virtual environment was designed with an intent to unite elements of familiarity and futuristic novelty. The virtual environment contained two large, holographic information panels modeled after the tile-display wall present in the physical testing environment. After remaining in the virtual environment for approximately one minute, two large gallery windows would open to reveal an outer-space Earthscape vista.

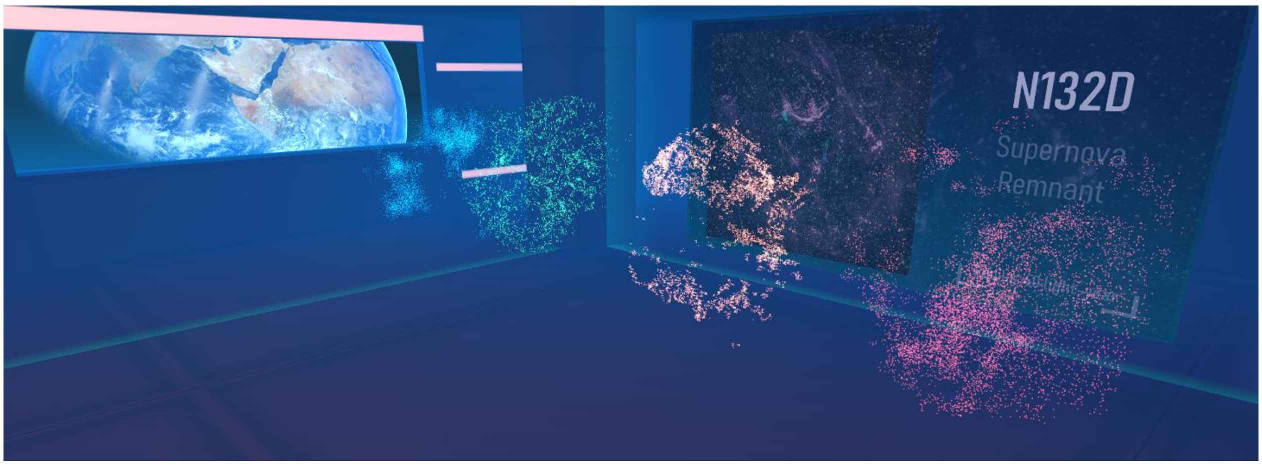


Figure 3.4 Four idle point cloud models in the virtual environment (left to right): N132D (blue), Crab Nebula (green), Cassiopeia A (yellow), E0102 (red)

3.2.7 Avatars in the Virtual Environment

Participants viewed each other as flat-shaded, head-and-shoulder avatars wearing VR HMDs with two googly eyes (see figure 5.1). Hands were represented using 3D models of their Oculus Quest hand controllers.

3.2.8 Debugging the Virtual Environment

To improve the process of development, Unity’s debug events were forwarded to a console visible in the virtual environment. It was primarily used to display logs of input-states and device connectivity.

3.2.9 Interactive Tools of the Virtual Environment

Users in the simulation were provided with the capability to interact with portions of the virtual environment. One such interactive tool allowed users to draw in the air by pressing the trigger on either or both of their hand controllers. This functionality was referred to simply as "Whiteboarding". Whiteboard sketches were visible to all other collaborators and remained for approximately 90 seconds, after which they would begin to disappear. This tool was particularly useful for emoting and diagramming spatial concepts.

The application provided users with the ability to move, rotate, and scale datasets in the virtual environment. This mode of interaction was referred to as "Grappling". When in grapple mode, colored widgets would attach to the center and corners of each model's rectangular bounding volume to indicate the model was available for interaction. Users could grapple a dataset by swapping their interaction mode and squeezing the primary trigger while reaching into a dataset. Once grappled, the dataset would remain parented to the controller until the trigger was released. Grappled datasets would inherit any change in position or rotation made by the parent controller. Datasets could be scaled larger or smaller by pressing up or down on the joystick of the parent controller. A lower limit threshold prevented datasets from becoming lost to infinitesimal scale. Grappling operations could occur using either hand. Therefore, two datasets could be grappled simultaneously if both controllers were used for selection.

Network design of the application limited users to grappling only the datasets which they had instantiated. Because the host machine was responsible for instantiating each dataset during testing, grappling was placed off-limits for the collaborative sessions.

3.2.10 File Output

The application's desktop environment supported exporting surface mesh data to various file formats, including Polygon File Format (.ply). The .ply file format provides a simple description of 3D geometry as an array of polygons. It is recognized by various model viewing applications, including MeshLab (Cignoni, Callieri, Corsini, Dellepiane, Ganovelli, & Ranzuglia, 2008), a free, open-source application used during initial experimentation.

3.2.11 Legacy Iterations

Previous iterations of this application were built to utilize a fleet of Oculus Go headsets mounted with OptiTrack motion-capture sensors to achieve precise, submillimeter, 6-DOF tracking. An even more precursory version of this technology was implemented using Google Cardboards housing an Android smartphone running a molecular visualization app with an HTC Vive puck mounted atop to provide spatial tracking. To properly enable spatial tracking using third-party devices, it was crucial to know the offset vector between the tracking device and the virtual camera's center origin. Failing to accommodate for the orientation and offset of the mounted tracking device would result in erroneous or sub-optimal spatial tracking. Using delayed or inaccurate tracking data can accumulate significant disorientation onto participants and lead to sensations of simulator sickness.

Figure 3.5 Dr. Dan Milisavljevic (front left) guides three students on a tour of the virtual environment using OptiTrack-mounted Oculus Go HMDs (legacy iteration)

3.3 Methods

The goal was to perform a mixed-methods study of user experience. These items detail the provided experimental setup, depict the tools and technology, diagram programming and engineering patterns. A qualitative approach has been taken here to create a "complete, detailed description" (Langkos, 2014, p. 5) of the experiment.

The Center for Innovative Research and Teaching at Grand Canyon University attributes unique weaknesses to both quantitative and qualitative research. “Mixed method strategies can offset these weaknesses by allowing for both exploration and analysis in the same study.” (“Overview of Mixed Methods”, n.d.). In this study specifically, it provided context to the research findings. Quantitative elements of the study included the collection and statistical analysis of pre-established Likert-type questionnaires. These questionnaires evaluated the workload and user experience of the testing sessions.

3.4 Activity

Participants were allotted fifteen minutes together in the virtual environment to investigate the supernovae datasets in whatever manner they chose. They were informed to expect similarities and differences in patterns within and across datasets, but not given any further instruction for how to interpret them. This left the participants free to engage with each other and the virtual environment using their own discretion. After the session, they completed a set of post-activity questionnaires relating to their experience in the collaborative virtual environment.

3.5 Variables

The research measured the perceived workload and user experience of participants who engaged in collaborative data exploration using lightweight co-located virtual reality devices. These variables included self-report measures of physical demand, mental demand, temporal demand, performance, effort, frustration, presence, engagement, immersion, discomfort, and experience.

3.6 Psychometric Tools

The Workload and User Experience of participants were measured using the NASA Task Load Index (TLX) (Hart, 1986) and a modified version of the Unified User Experience Questionnaire (Tcha-Tokey et al., 2016) respectively. The NASA TLX has accumulated significant popularity across a variety of domains since its introduction in aviation human factors research nearly twenty years ago (Sauro, 2019). These two questionnaires were selected on the criteria of their minimal length, ease of administration, and relevance to our research questions. Both surveys were administered with pen and paper then transcribed to digital .csv file-format.

3.6.1 NASA Task Load Index (TLX)

The NASA Task Load Index is a six-item subjective-rating questionnaire which measures the perceived workload of a given task (Hart, 1986). These measurement items include Mental Demand, Physical Demand, Temporal Demand, Effort, Performance, and Frustration. Each item is rated from low to high on a 21-point scale. Responses for each item are transformed into a 100-point score by subtracting a point and scaling by a factor of five.

3.6.2 Modified User Experience Questionnaire (UXQ)

The Unified User Experience Questionnaire measures user experience in immersive virtual environments (IVEs) uses ten subscales, including Presence, Engagement, Immersion, Flow, Usability, Emotion, Skill, Emotion, Judgement, Experience Consequence, Technology Adoption (Tcha-Tokey, Loup-Escande, Christmann, Richir, 2016).

They note that one limitation of their proposed questionnaire to measure User Experience in virtual environments “concerns the lack of investigation of other reliability parameters, such as the test-retest method, due to the already big workload for the participants requested by our experimental protocol." (p. 21). However, they state it “may be extended to different types of VE ... such as therapeutic, design or collaborative applications” (Tcha-Tokey et al., 2016, p. 22).

The questionnaire was selected for its ability to sample a palette of user experience dimensions with brief sections. To narrow scope and economize the length of testing, four of the subscales most closely matching our research criteria were selected and appended with a single item subscale measuring prior experience with virtual reality technologies. This narrowing of scope avoided the administration of subscales that were either inapplicable or irrelevant to the research inquiry. We scored on a 5-point Likert scale as opposed to the original 10 (p. 4) to increase ease of use for testers.

The questions were further adapted to reference the modern style of input devices that participants would be using (e.g., spatially-tracked hand controllers instead of a gamepad controller, ambulatory movement instead of joystick input, etc.). The modified version of the questionnaire used in this study contained 31 items spanning five total subscales (Presence, Immersion, Engagement, Consequence, and Experience).

"Consequence" in our modified context refers to the original dimension "Experience Consequence" (Tcha-Tokey et al., 2016), the simulator sickness factor measured by the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993).

Subscale Critique

The lowest reported value in the immersion category was item no. 21 which stated: "I got scared by something happening in the virtual environment" (Tcha-Tokey et al., 2016).

We propose that this item describes an immersive quality in games and simulations, however it is not suitable for all virtual environments. In *Proposition and Validation of a Questionnaire to Measure the User Experience in Immersive Virtual Environments*, Tcha-Tokey, Christmann, Loup-Escande, and Richir (2016) note that "this UX questionnaire is a non-definitive tool and still needs adjustments" (p. 20). In this specific context we are inclined to agree. Were this questionnaire to be revised, it could be worth evaluating the effect of removing or conforming this item to match the context of the virtual environment (i.e., one which still maps adequately to Immersion). For a setting in which fear is not considered an immersive quality (such as in data visualization), this item would likely elicit low or confused responses even if immersion in the VE were high.

The mean response to item no. 21 on the UXQ was calculated (M = 1.68, SD = 0.98, Mode = 1). Removing the item from the questionnaire increased the mean Immersion score and reduced the standard deviation of responses within the subscale from (M = 3.32, SD = .79) to (M = 3.60, SD = .35). The correlation matrix of UXQ responses (see figure 4.2) indicates little correlation between item no. 21 and the other items of its subscale (items 16 to 22). To avoid interfering with the original inventory's psychometric properties, we elected for this question to remain.

3.6.3 Variable Mapping

Survey Instrument (Abbreviation)	**Measurement (*Subscale Dimensions*)**
Modified User Experience Questionnaire (UXQ)	User Experience (*Presence, Immersion, Engagement, Consequence, Experience*)
Unweighted Pen & Paper NASA Task Load Index (TLX)	Workload (*Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, Frustration*)

3.7 Sample Selection

The sample being investigated was selected through non-probabilistic convenience sampling. Participants were retrieved from a pool of visiting faculty, laboratory assistants, and classes of approximately 600 students available within Physics and Astronomy at Purdue University. They were anticipated to have minimal experience with data visualization in virtual reality.

3.8 Ethics

Testing protocol for human subjects was audited and cleared with the Purdue IRB ethics committee before subject recruitment began. In compliance with ethics, test subjects were voluntary participants whose identifiable information was anonymized and stored for the length of twelve months after collection. Participants were free to withdraw from the study at any time, particularly if they expressed symptoms of simulator sickness (Kennedy, Lane, Berbaum, Lilienthal, 1993).

3.9 Recruitment

Recruitment occurred in multiple waves over the course of several weeks, with three waves of testing performed in total. Recruitment materials were presented before four separate sections of a 200-level physics course (PHYS 220) at Purdue University prior to the start of lecture. A verbal statement provided a description of the goals, duration, and voluntary nature of the research. This information was provided along with an overview of eligibility, a link to an online sign-up sheet, and an email contact. Students were invited to reserve a spot using an online signup sheet, prioritizing groups which had not yet been filled.

3.10 Testing Sessions

Participants began by arriving at Purdue University's Envision Center shortly before their scheduled testing session. As this research aimed to observe co-located collaboration, testing only occurred if two or more of the participants arrived for their testing session. To maintain the testing schedule and avoid interruptions, sessions were set to commence without any individuals who were more than fifteen minutes late.

The testing environment was set in a large, quiet, isolated space reserved for the researcher team and research subjects. Before each session began, participants sat down to read over the consent form detailing their rights as a testing subject. After all consent forms were signed, participants were provided with a brief introduction to the laboratory, the nature and duration of the study, and the technologies they would be using.

Each participant was provided an Oculus Quest VR headset pre-calibrated to a common tracking space using standard Oculus calibration settings and connected to the same PC server. Before entering VR, participants received a demonstration of their input devices and how to properly adjust the fit of the headset. Testing sessions lasted fifteen minutes in total and began once all the participants felt accommodated wearing their device.

Each testing session commenced by starting a fifteen-minute timer and introducing the set of supernova-remnants into the collaborative virtual environment. Participants were able to walk and speak freely alongside each other or explore the data at their own pace throughout each testing session.

After the allotted fifteen minutes, participants were remotely disconnected from the application and informed to place their devices on the floor. Subjects promptly returned to their writing stations to complete two questionnaires relating to their experience within the CVE. Once all participants had completed the assigned questionnaires they were debriefed and dismissed from testing.

CHAPTER 4. RESULTS

4.1 Building the Virtual Environment

4.1.1 Equipment and Expertise

The construction of a collaborative virtual environment requires the orchestration of several hardware and software systems. The following is minimally necessary to build a custom CVE:

A VR-ready development PC, a set of mobile VR HMDs (Oculus Quest, Oculus Go, Google Cardboard, etc.), 6-DOF spatial tracking support (HMD integrated, OptiTrack SDK, Vive Pucks, etc.), a VR-supported development engine (Unity, Unreal Engine, etc.), IDE software (Microsoft Visual Studio, MonoDevelop, Xcode, etc.), a 3D modeled virtual environment, a VR API (Oculus SDK, OVR, SteamVR etc.), a networking API (Engine integrated, Lidgren, Photon, etc.), a standard WiFi router, and a lead programmer to coordinate development.

The lead programmer will need to have familiarity with conventional network and simulation programming patterns. The complexity of development will depend largely on the level at which the systems are implemented (i.e., high vs low level APIs). Additional steps are required if the VR HMDs do not natively support 6-DOF tracking. See section 5.7 of the appendix to view a detailed map of the technologies used in the production of this application.

4.1.2 Enabling Third-party Tracking Solutions

If 6-DOF tracking is not supported, the development team will need to stream tracking data to the HMD using a third-party device. Using this approach requires additional time and information to set up (e.g., the offset and orientation of third-party tracking devices must be brought into account).

To illustrate an example, earlier iterations of this project utilized infrared OptiTrack beacons to provide full 6-DOF tracking capabilities to a fleet of 3-DOF Oculus Go HMDs. Beacons were fastened to 3D-printed mounts which were attached to the front of each headset (see figure 3.5). The position of each tracking beacon was collected by an array of sixteen OptiTrack motion-capture cameras spaced evenly around the perimeter of the testing environment. An additional computer on the network processed the raw camera input as coordinate information and sent it wirelessly to the HMDs. Each tracking beacon was assigned an ID in Motive and coupled to an Oculus HMD running the OptiTrack SDK in Unity. This method delivered highly accurate, stable, low-latency spatial tracking, however it required substantial hardware and software infrastructure.

As demonstrated in the example, the position of each beacon was only read by the headset intending to use the tracking data. Although headsets could freely read the tracking data of any other beacon (i.e., the position of other users), we chose to rely on the simulation server to pass position data between clients. The decision to make the virtual environment agnostic to its tracking system was later validated by the minimal setup required to transition to Oculus Quest (capable of supporting its own tracking).

4.2 Modified User Experience Questionnaire (UXQ)

Each individual was assigned a score for each user experience subscale by averaging their responses within subscale categories and accounting for response directionality. The user experience dimensions measured using the Modified User Experience Questionnaire (UXQ) follows:

User Experience Subscale	Mean	Standard Deviation
Presence	4.26	0.44
Immersion	3.32	0.70
Engagement	4.39	0.61
Consequence	1.91	0.57
Experience	3.40	1.69

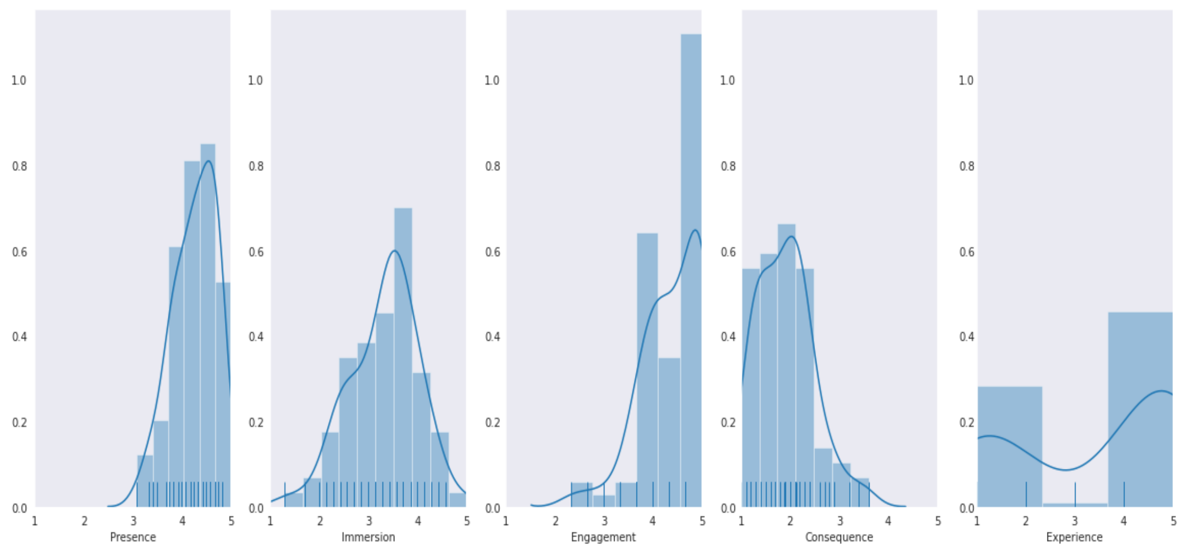


Figure 4.1 Kernel density estimate of the Modified User Experience Questionnaire (UXQ) subscales

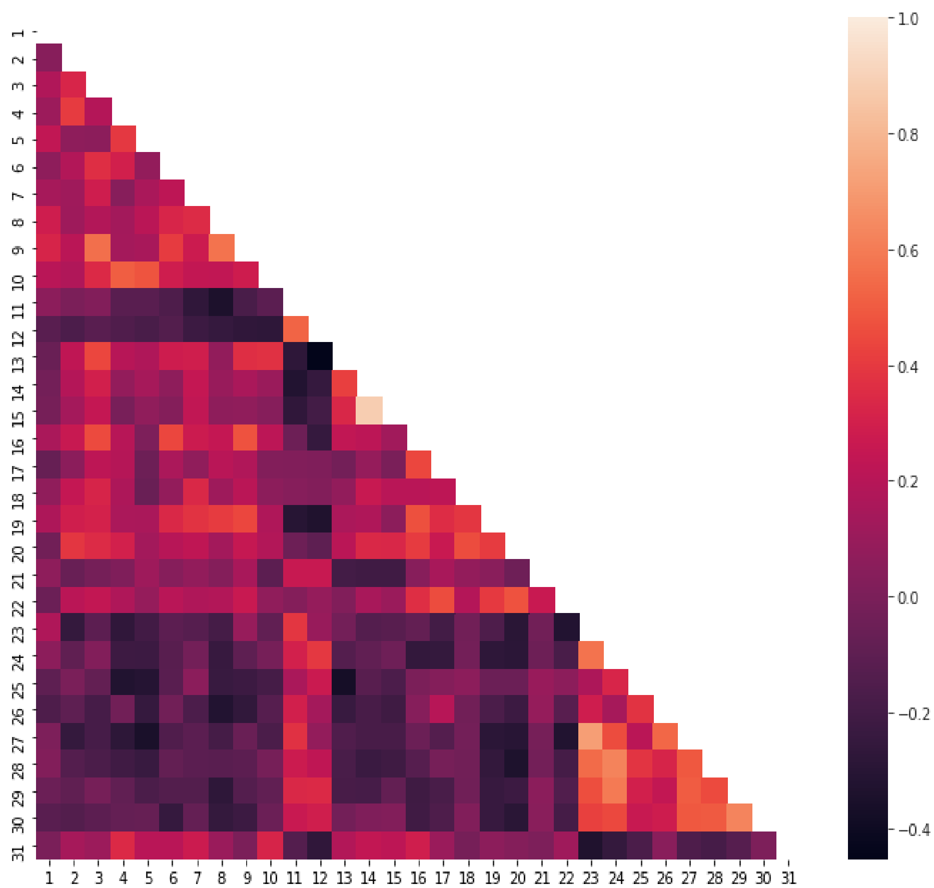


Figure 4.2 Correlation matrix of the Modified User Experience Questionnaire (UXQ) Responses (see appendix section for question mappings)

The correlation of each UXQ item with every other UXQ item can be seen using the correlation matrix above (figure 4.2). The brighter or darker the cell, the stronger the positive or negative correlation respectively. The matrix is in lower triangular form because it is square and symmetrical across the diagonal.

4.3 NASA Task Load Index (TLX)

The perceived workload measured using the NASA TLX follows:

NASA Task Load Index (Dimension)	Mean	Standard Deviation
Physical Demand	30.65	22.17
Mental Demand	18.51	17.81
Temporal Demand	14.29	14.32
Performance Level	29.94	19.91
Effort Level	25.13	18.01
Frustration	14.42	17.49

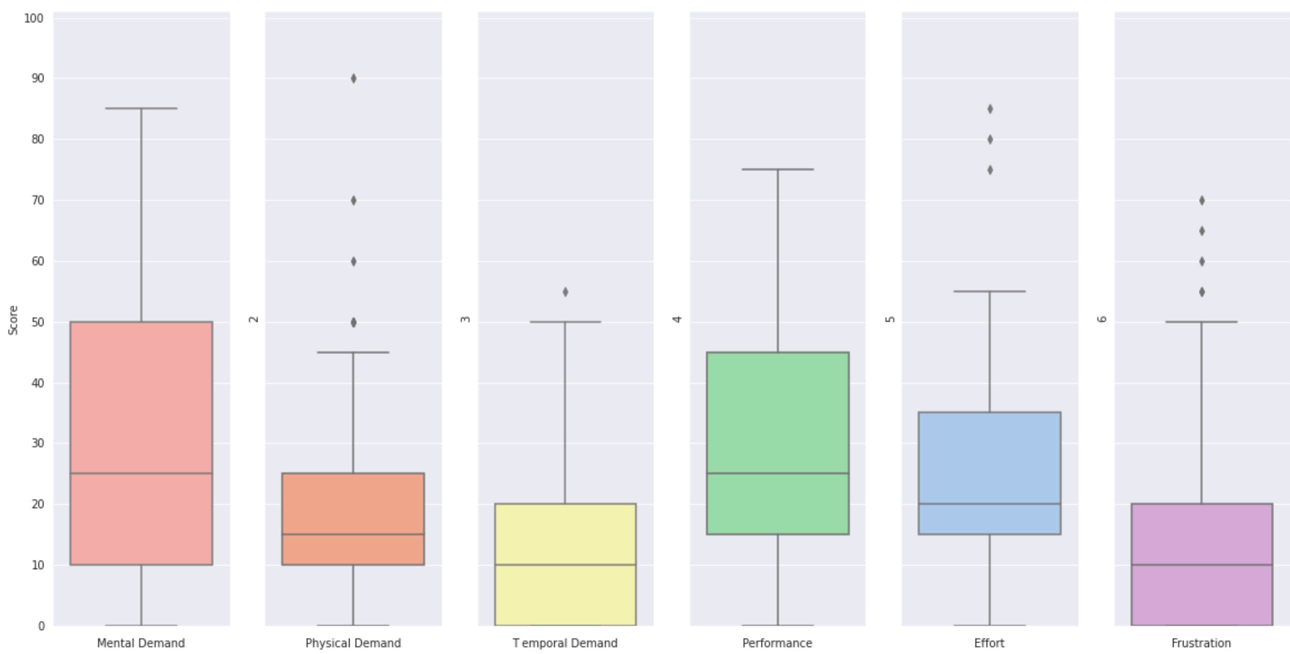


Figure 4.3 Box plot of NASA Task Load Index (TLX) Scores

4.4 Pairwise Comparisons (TLX & UXQ)

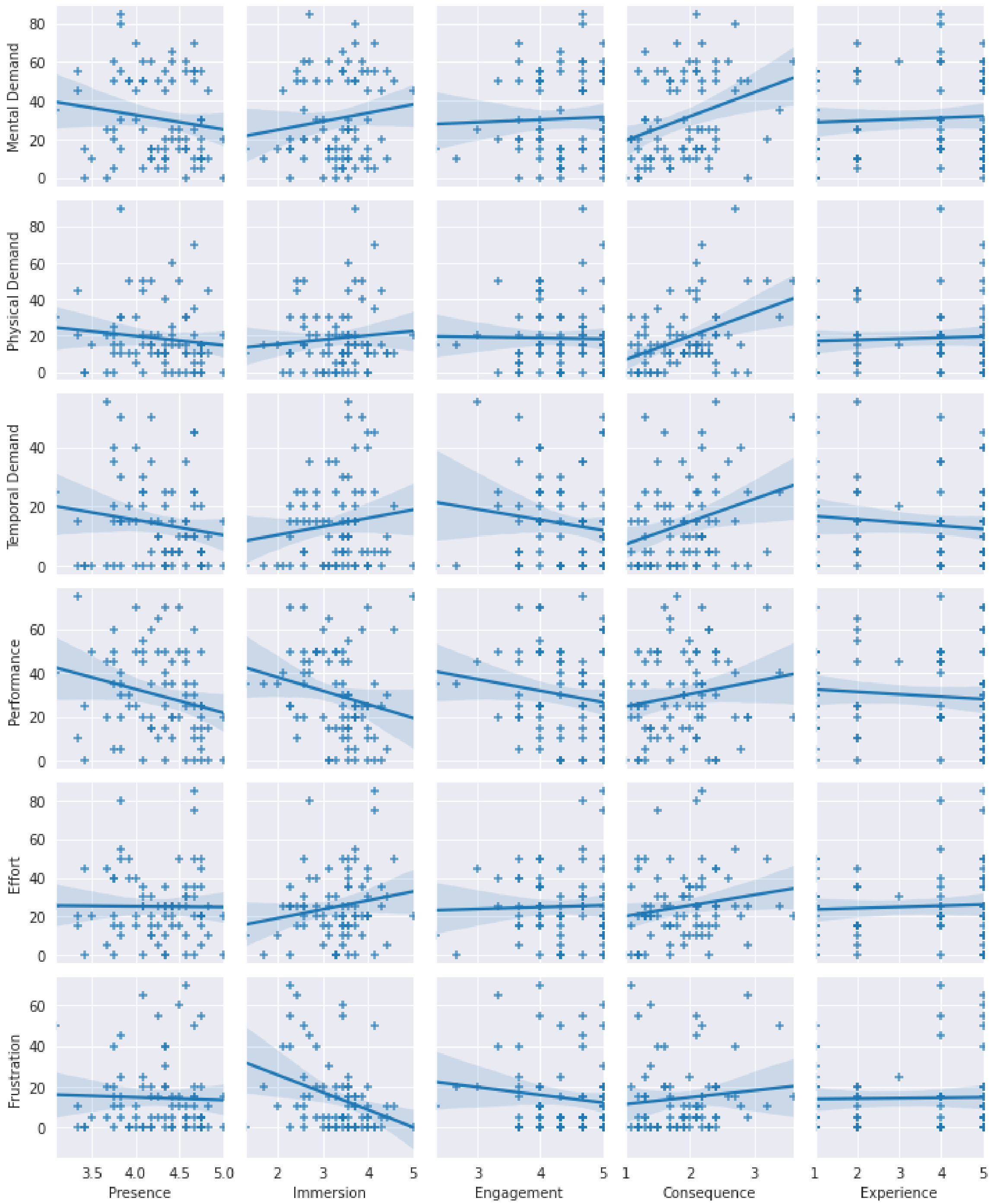


Figure 4.4 Pairwise regressions of the NASA Task Load Index (TLX) versus the Modified User Experience Questionnaire (UXQ)

4.5 Analysis

4.5.1 Analysis of the Modified User Experience Questionnaire (UXQ)

We found the co-located collaborative environment was positively received. Participants reported moderately high levels of presence (85.2% agreement) and engagement (87.8% agreement), moderate levels of immersion (66.4% agreement), and moderately low levels of consequence (38.2% agreement). No participants requested to be removed from testing.

Higher scores of user experience would signify that participants felt more able to focus on the virtual environment and utilize their senses accurately. This informs our research team that groups felt a compelling sense of agency (i.e., an ability to explore and interact freely) and involvement in the virtual environment. Lower values would have indicated that other factors (such as nausea or distraction) had diminished the experience of using the VE.

Since the Oculus Quest HMD tracks natural head and body movement it was anticipated the average UX score would remain moderately high. Had the locomotion used joystick vection we might have expected the values to be lower. However, this remains speculative.

4.5.2 *Post Hoc* Evaluation of the Derived UXQ

In a 2017 study at Arts et Métiers ParisTech, *Effects on User Experience in an Edutainment Virtual Environment: Comparison Between CAVE and HMD*, Tcha-Tokey et al. detail the results of using the Unified User Experience Questionnaire used to compare User Experience dimensions between CAVE and HMD systems. We reason that these results provide an appropriate baseline for a *post hoc* evaluation.

According to their research, HMD users wore a VR ONE mobile headset housing a Samsung Galaxy S6. Their EON ICUBE CAVE "composed of four walls … delimiting a 10- by-10-foot room with projectors aimed at each wall and …. trackers to track the stereoscopic 3D glasses" (p. 4). Throughout testing, "each of the 21 participants tested [both] immersive devices [in random order] and filled the same UX questionnaire ... for each device" (p. 5).

Participants in the study used the "edutainment 'King Tut VR2' application designed by the EON Reality SAS company." where "the goal of the … application is to relive the journey of Howard Carter and his discovery of King Tutankhamun's tomb." (p. 5). Participants in their study spent an average of approximately 11 minutes in the CAVE (657.10 sec) and 12 minutes in the mobile HMD (724.52 sec) (p. 6). They state, "the aim of the study [was] to compare the effect of two virtual devices on user experience in an edutainment virtual environment." (p. 2). They found their hypothesis that "subjective user experience [was] greater in the CAVE than in the HMD Mobile" was partially validated (p. 6). They reported Presence, Engagement, Flow, Skill, Judgement, and Experience Consequence to be significant at the ($p < .05$) level (p. 1).

The following chart provides a *post hoc* evaluation of our results alongside theirs, featuring the four UX subscales derived from their original questionnaire: Presence, Immersion, Engagement, and (Experience) Consequence. Our scores were transformed to match the 10-point range of the original questionnaire.

User Experience Subscale	Device	Mean	Std. Dev	*Post Hoc* Comparison
Presence	**Quest**	**8.52**	**0.88**	*
	CAVE	7.40	0.91	
	ONE VR	6.07	1.35	
Immersion	**Quest**	**6.64**	**1.40**	*
	CAVE	6.30	1.70	
	ONE VR	4.90	1.70	
Engagement	**Quest**	**8.78**	**1.22**	*
	CAVE	7.58	1.52	
	ONE VR	6.30	1.70	
Experience Consequence	Quest	3.82	1.14	
	CAVE	**2.18**	**1.15**	*
	ONE VR	4.02	1.74	

Figure 4.5 *Post hoc* evaluation of transformed UXQ results with *Effects on User Experience in an Edutainment Virtual Environment: Comparison Between CAVE and HMD* (Tcha-Tokey, Christmann, Loup-Escande, Richir, 2017, p. 5-6)

We include this comparative evaluation to contextualize the Modified User Experience Questionnaire (UXQ) by comparing it with the overlapping measures of the psychometric tool from which it was derived (i.e., how do these findings relate to the literature).

We reason that despite dissimilarities in motivation and methodologies between these studies, the derived psychometric evaluations are adequate for comparison. Both studies measured the user experience of immersive VR technologies; however there was significant contrast between the tiers of HMDs used in testing (integrated consumer device vs. dedicated consumer hardware). Both studies evaluated academic-level participants, used investigative VR content, and spent similar lengths of time in the virtual environments (approximately 7-18 minutes) (p. 2-3).

However, while CAVE theaters are considered collaborative environments (Defanti et al., 2011), users in their study participated on their own for both VR treatments (p. 3). Therefore, they were not subject to social presence in the VE. Moreover, the ONE VR HMD did not support external input devices and was limited to 3-DOF tracking (p. 4). Similar to our application, there were both active and passive interactions in the VE (p. 5).

4.6 Transcription, Storage, and Excluded Observations

Handwritten responses to the questionnaire scales were transcribed into Google Sheets, a free online spreadsheet application provided by Google. The transcribed responses were stored on a password-secured account linked to Google Drive.

From the 78 initial observations, one was excluded because they had already participated during a previous testing wave. The latter observation was excluded from transcription and analysis.

4.7 Statistical Software

Results of the NASA Task Load Index (TLX) and the Modified User Experience Questionnaire (UXQ) were analyzed using Seaborn, a high-level statistics API for Python. The Seaborn library was imported into Colab, a free and online Google Research product “well suited for data visualization” ("Colaboratory FAQ", 2019). Colab allows anyone to create collaborative Python notebooks with access to remote computing resources provided by Google.

CHAPTER 5. CONCLUSION

5.1 Discussion and Future Research

The observations and application of this collaborative VR modality have presented compelling insights to our research team. Certainly, incentive remains to implement and investigate collaborative virtual reality wherever users may benefit from engaging with a virtual environment and each other simultaneously.

We addressed two primary dimensions of the problem of collaborative data visualization and analysis as follows: [1] we detailed the implementation of a novel co-located VR hardware and software system, [2] we conducted a formal user experience study of the novel system using the NASA Task Load Index (Hart, 1986) and the Modified User Experience Questionnaire, a new user study tool based upon the Unified User Experience Questionnaire (Tcha-Tokey, Christmann, Loup-Escande, Richir, 2017) to empirically observe the dependent measures of workload, presence, engagement, consequence, and immersion. This study was observational rather than experimental. We described the implementation of the study and user reactions to the technology that was created.

5.2 Discussion on Testing Observations

5.2.1 General Device Setup

While there is good intention behind displaying the input devices for novice users, we found it was important for participants to hold the devices in their hands prior to instruction. It is clear to reason that participants are less likely to gain an understanding of their input device if they have not been given the opportunity to form a tactile map of its layout. This challenge is not endemic to virtual reality specifically but is common in gaming more generally. Video-essayist Razbuten conducted a series of in-depth case studies on how videogames are viewed from the perspective of a novice and used his wife as the research subject. In *What Games Are Like For Someone Who Doesn't Play Games* (2019), he discussed the difficulty of learning to use input devices, saying:

> I know that figuring out a game's controls sounds easy, but she essentially had to not only memorize which buttons did what, but also which buttons were where, adding another layer of things to keep track of and making the process a little bit more overwhelming. She typically fared better with games that didn't give too much information to remember." (Razbuten, 2019).

The challenge of learning how to use a new input device is further complicated for VR users by their inability to see the external world while wearing an HMD. This makes instruction and assistance unwieldy or inefficient.

Introducing many individuals to virtual reality quickly and efficiently was a challenge of its own. We observed the most effective way to introduce an aggregate of novice users to the technology was by having them hold their input devices to mimic button actions while they were being provided with an overview of the controls. This provided participants with an opportunity to form a tactile understanding of the input devices before they entered into the virtual environment. First time users would often experience difficulty relating back to what they had been shown if they did not receive instruction in this manner.

It is worth exercising patience with novice users and backing them out entirely if further clarification is needed. For many, entering the virtual environment was a natural and intuitive process while others required additional guidance. It was considered reasonable to expect mistakes from users even when provided explicit instruction. For example, it was not uncommon to see participants start out by holding their VR controllers upside down. For some users, it was useful when concepts were related to elements of similar input devices (such as a Nintendo Wii Remote).

Instead of relying on participants to recall extensive information upfront, it was generally better to provide users with the opportunity to gain first-hand experience with the virtual environment. An explanation which extends too long may be better suited as a demonstration.

5.2.2 Objects of the Mundane

A small watercooler sat alongside a wall just outside of the bounds of the virtual playspace. Though the prop lay idle and inaccessible, it received a disproportionately high weight of positive attention from those entering the virtual environment. The nature of individual attention given to this commonplace item was suggestive of an inclination toward familiarity in novel environments.

We were left with the impression that these commonplace “objects of the mundane” may help to introduce a valuable feeling of familiarity during largely novel experiences.

5.2.3 Expressions and Utterances

A majority of groups expressed they had enjoyed the experience of virtual reality, the virtual environment, and their ability to interact with one another. Many individuals described their ability to freely navigate the VE with their body as compelling and enjoyable. Those non-accustomed to stereoscopic digital displays appeared particularly impressed by the presence and fidelity of objects in 3D virtual space. Some participants claimed they wished they could remain in the virtual environment longer and demonstrated reluctance exiting the application.

Upon transitioning out of the virtual environment, users would often look towards one another with exaggerated facial expressions and utterances of marvel and bewilderment. Most participants found themselves standing in a new location from where they began and it was common for them to express that they had entirely forgotten about their orientation within the physical environment.

5.2.4 Representations

Users often began categorizing datasets based on the characteristics which could be observed. Some hypothesized significance to arbitrary elements, such as the color assigned to each dataset. These observations often led to the start of conversations which proposed various explanations. Once participants were comfortable sharing one observation it appeared to facilitate the generation of further hypotheses.

The linear placement of the datasets had lead several groups of participants to attribute temporality to each supernova event, though it wasn’t uncommon for these discussions to reach a general consensus regarding their ordering. Oftentimes these conversations were aided by whiteboard drawings which were used to leave notes and express larger ideas.

The notion that the datasets were of a single supernova event across time was ultimately misguided, however it served to rebound the conversations toward other topic areas. For example, comparing datasets through the lense of a timeline would lead to questions regarding the relative scale of each dataset. Many who discussed the regularity in size between datasets would later hypothesize how their sizes might compare in actuality.

To avoid interfering with the pacing and content of discussions among groups in the virtual environment, an effort was made on behalf of the research team not to interject with information on the validity of group discussions. If it became evident a group was genuinely curious, or if participants addressed the research team directly, an elaboration was provided after the debriefing.

Figure 5.1 Three participants use the Whiteboard tool to doodle in the virtual environment.

5.2.5 Whiteboarding

Participants would often begin their collaborative session by creating doodles for each other or mirroring hand motions to draw symmetrical patterns. Many expressed the whiteboarding tool was an intuitive extension of their input devices. Some spent significant time experimenting with how it could be used to measure or highlight features of the datasets.

Many of the participants demonstrated how they enjoyed painting words in the virtual environment and bobbing around to observe the skewed perspective-alignment of their drawings. It was often surprising for participants to experience the challenge of aligning their writing across 3D space without a 2D surface to guide them. It's uncommon for us to view our markings suspended in space, hence it was reasonable for many drawings to appear sloppy or distorted from other perspectives. This adheres closely with what was noted in a 2017 study carried out by the MIT Media Lab at Cambridge University. In their study *Investigating Social Presence and Communication with Embodied Avatars in Room-Scale Virtual Reality* (Greenwald, S. W., Wang, Z., Funk, M., & Maes, P., 2017) they note:

> Nearly all participants described drawing in 3D as challenging, but some enjoyed the challenge while others found it frustrating. There was broad agreement that drawing in 3D was typically slower, but there were cases where it offered advantages. The biggest challenge was becoming accustomed to considering multiple viewing perspectives. (Greenwald et al., 2017, p. 11)

On several occasions, players invited each other to play games using their whiteboarding abilities. For example, there were multiple individuals who spontaneously drew a board of tic-tac-toe and made their first move. Some groups began impromptu games of charades carried out by drawing 3D pictograms. These emergent social interactions were fascinating to watch and suggested the presence of a deeper social landscape. All but one group managed to overcome the temptation of drawing vulgar icons in the virtual environment.

5.3 Experience Distribution

We assumed the distribution of experience level was bimodal because virtual reality technologies have yet to become mainstream and widely adopted. Participants reported significant experience using virtual reality technologies or almost none at all. This is believed to have led to fewer responses between the extremes.

5.4 Discussion of Pairwise Regression of TLX and UXQ

Pairwise analyses between the TLX and UXQ demonstrated several interesting and unsurprising relationships. For example, users who reported higher levels of Consequence (Simulator Sickness) on the UXQ also tended to rate higher levels of overall TLX Workload (particularly for Mental, Physical, and Temporal Demand). Both measures evaluate factors related to mental and physical stress in the virtual environment, therefore it was reasonable to have anticipated a positive correlation across both sets of dimensions.

Interestingly, prior experience with virtual reality technologies showed almost no effect on the overall workload measure of participants. There may be several reasons to speculate why this was. For one, participants were not required to perform any setup themselves and received continual guidance entering and exiting the virtual environment. Furthermore, participants in the virtual environment were not required to navigate any user interface menus or interact strategically with their input devices. Therefore, the task given to participants did not lean on having any prior VR experience. It's likely that users with VR experience might bring along a set of expectations which would be otherwise advantageous (e.g., knowing how to navigate menus). Because testing sessions were brief, social, largely explorative, and involved no complex VR interactions, the effect of prior experience with VR technologies on workload appears to have been minimized.

The TLX Frustration dimension was most strongly and negatively correlated with UXQ Immersion. Users who reported higher levels of Immersion on the UXQ tended to rate lower levels of Frustration on the TLX. In reverse, higher levels of Frustration were attended by lower levels of Immersion. While this does offer the interpretation that users become less frustrated as they immerse in a virtual environment, it seems more reasonable to suggest that frustration acts to inhibit a user's sense of immersion. For example, if a user becomes frustrated progressing towards their desired goal, they may need to remove themself from their virtual context to contemplate a solution. Uninhibited, users would be less likely to encounter barriers which remind them that what they're interacting with is not "actually there." If a problem is embedded at a higher level of abstraction it may be necessary to advance up the hierarchy of abstraction to where it may be solved (e.g., no interface element may be able to assist with a headset that's not been fitted properly). In principle, this requires that one abandon or suspend their current state of immersion.

While other dimensions of workload may be viewed in a positive manner by participants (e.g., I'm a hard worker, I take my time with my work, I think deeply about my work), frustration remains a largely negative emotional state. Controlling for frustration is crucial to ensuring participants do not elect to give up.

TLX Frustration was also negatively correlated with UXQ Engagement, though to a lesser degree. Engagement relates to one's ability to become involved and interact with the engaged content. For example, watching a documentary on a large display with high-quality surround sound may feel highly immersive (i.e., it compellingly stimulates multiple senses simultaneously), but it would not be considered engaging in this context. The correlation for this variable may be postulated for reasons similar to Immersion (i.e., frustration acts to inhibit engagement). However, it could be the case that a participant's perceived lack of engagement could contribute to feelings of frustration as well (e.g., I was not included in the discussions, my considerations were not taken seriously, I felt ignored or rejected by others).

5.5 Additional Applications

There are no shortages of application for co-located virtual reality technologies. The wider social implications of this technology have yet to be fully determined. In several years time we may find such a technology has evolved into a ubiquitous facet of the virtual reality ecosystem where it may be taken for granted. We know for certain this technology is well under development in the fast-paced world of entertainment. I-Illusions, the studio accredited with the development of the popular VR title "Space Pirate Trainer" (I-Illusions, 2017) is already publishing content about a prototype form of VR lasertag titled "Space Pirate Arena" (Melnick, 2020). Unlike the interior of standard arcades, these experiences occur within a large and featureless space ripe for virtual environments. This particular implementation of co-located virtual reality is referred to as "hall-scale VR" and is described by I-Illusions as "a glimpse into the future of lasertag" (2020).

Many academics will be familiar with halls in the higher-educational setting. Displays of knowledge proceed creatively before forums of thousands every year within university lecture halls. Students are challenged to reify high-level learning concepts with educators in laboratory settings. Innovation within chemistry, physics, and engineering very often involve overcoming and leveraging the constraints of the physical world. While the physical reality of these phenomena may remain unchanging, the models we procure to represent them need not. Indeed, some phenomena are only understood to the degree to which they can be modeled.

The first iteration of our collaborative technology was motivated to reconcile the lack of perspective and limited agency afforded to non-HMD spectators viewing visualizations of protein molecules on display at our laboratory. Immersive technologies enable scientists to shrink to nanoscopic scale to study the composition of molecules or travel to normally inaccessible regions of the universe to examine structures spanning vast regions of space. Adding social presence to the mix seems only natural. Dr. Milisavljevic of Purdue University wrote of the project's early stages:

> Experiencing data in VR revealed and/or highlighted new relationships that were not obvious from the animations I had made. I have found that actively manipulating 3D content while changing viewing angle is the best way to interpret the 3D morphology of stellar debris. The VR experience is the most powerful way for me to do this. I'm excited about collaborative VR because we will have the shared experience of changing perspective and manipulating 3D content (D. Milisavljevic, personal communication, February 2, 2019)

Figure 5.2 Composite rendering of four co-located participants viewing supernova remnant E0102 using Oculus Quest HMDs

Physical and digital simulations are practical in the fields of science. They continue to develop as technological demand shifts the landscape of what we are able to model. Models in the scientific domain share a common need for controlled environments which may be dangerous, difficult, or impractical to reproduce naturally.

These virtual environments are particularly useful for personnel who work in hazardous environments. Modern state-of-the-art implementations of co-located VR training have been demonstrated by companies like V-Armed Inc., a “virtual reality technology company that specializes in military and law enforcement immersive training” (V-Armed, 2020). Like other companies, they combine their collaborative virtual environment with additional peripherals which heighten the utility and realism of their training simulations (e.g., haptic-enabled replica firearms). Their collaborative problem-solving exercises demonstrate several of the key benefits offered by virtual training systems broadly.

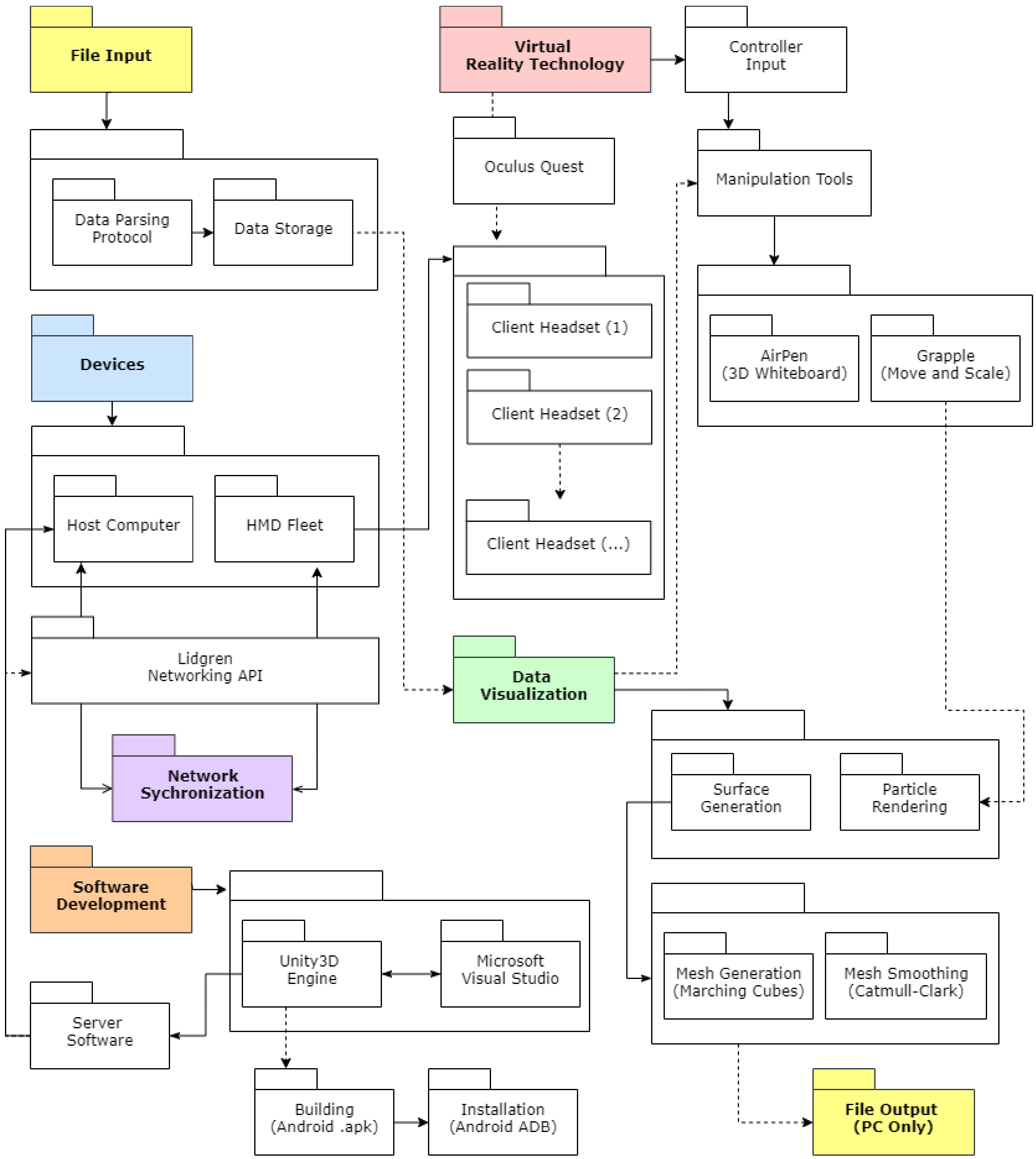
Similar to flight or medical training simulations, parameters within these virtual environments may be adjusted to match learning objectives in real-time. Virtual training simulations often provide participants with detailed recordings of their performance for later evaluation. Collaborative systems can seamlessly integrate these features in addition to metrics which detail the coordination and cooperation of participants in the CVE. Were it an objective of this research, our platform could have been easily modified to facilitate the creation of playback recording systems (viewable through video or from within the virtual environment itself).

These collaborative VR systems have the potential to be married to any number of evolving technologies seen today. The creation of our co-located CVE was an endeavor of its own, however future implementations of this technology could soon become effortless or device integrated. They could be crafted to take on smaller, more modular forms and proliferated throughout a wide array of applications across science and the arts.

For example, another application of our virtual environment was demonstrated during a lecture at Purdue University for students attending *AD 41700 Augmented & Virtual Reality Art*. This course "gives students the opportunity to create immersive Virtual Reality content … and explore the artistic and critical potential of AR and VR … researching both historical precursors and contemporary trends." (Winkler, 2019). Students coming to our laboratory brought in LIDAR scans of environments at Purdue University and used our platform to curate their results during a presentation. We were able to accommodate these new datasets and add additional effects (e.g., color and noise displacement) without needing to make any changes to the platform itself.

APPENDIX

Technical Diagram of Software and Hardware Components



Modified User Experience Questionnaire (UXQ)

Participants were asked to answer the following questions on a 5-point scale with 1 being "Strongly Disagree", and 5 being "Highly Agree". Note: Response items no. 11 and 12 measure an inverse relationship to their respective subscales and require their values be transformed in reversed for scoring.

No.	Questionnaire Items (5 Degree Likert-type)	*Subscale*
1	The virtual environment was responsive to actions that I initiated.	*Presence*
2	My interactions with the virtual environment seemed natural.	*Presence*
3	The visual aspects of the virtual environment involved me.	*Engagement*
4	My movement in the virtual environment seemed natural.	*Presence*
5	I was able to actively survey the virtual environment using vision.	*Presence*
6	The sense of moving around inside the virtual environment was compelling.	*Engagement*
7	I was able to examine objects closely.	*Presence*
8	I could examine objects from multiple viewpoints.	*Presence*
9	I was involved in the virtual environment experience.	*Engagement*
10	I felt proficient in moving and interacting with the virtual environment at the end of the experience.	*Presence*
11	The visual display quality distracted me from performing assigned tasks.	*Presence*
12	The devices (gamepad or controllers) distract me from performing assigned tasks.	*Presence*
13	I could concentrate on the assigned tasks rather than on the devices (gamepad or controllers)	*Presence*
14	I correctly identified sounds within the virtual environment.	*Presence*
15	I correctly localized sounds within the virtual environment.	*Presence*
16	I felt stimulated by the virtual environment.	*Immersion*

17	I became so involved in the virtual environment that I was not aware of things happening around me.	*Immersion*
18	I identified with the avatar I played in the virtual environment.	*Immersion*
19	I become so involved in the virtual environment that it is as if I was inside the game rather than manipulating a controller and watching a screen.	*Immersion*
20	I felt physically fit in the virtual environment.	*Immersion*
21	I got scared by something happening in the virtual environment.	*Immersion*
22	I became so involved in the virtual environment that I lost all track of time.	*Immersion*
23	I suffered from a headache during my interaction with the virtual environment.	*Consequence*
24	I suffered from eye strain during my interaction with the virtual environment.	*Consequence*
25	I felt an increase of my salivation during my interaction with the virtual environment.	*Consequence*
26	I felt an increase of my sweat during my interaction with the virtual environment.	*Consequence*
27	I suffered from nausea during my interaction with the virtual environment.	*Consequence*
28	I suffered from "fullness of the head" during my interaction with the virtual environment.	*Consequence*
29	I suffered from dizziness with my eyes open during my interaction with the virtual environment.	*Consequence*
30	I suffered from vertigo during my interaction with the virtual environment.	*Consequence*
31	I have had experience using virtual reality technologies in the past.	*Experience*

NASA Task Load Index (TLX)

Participants were asked to answer the following six questions on a 21-point scale, with 1 being "Very Low", and 21 being "Very High". Note: Responses for each item are transformed into final score values by subtracting a point and scaling by five to reach a value from zero to one hundred (i.e., A response value of 12 transforms to a score of 55). Optional score weighting steps were not used for this study.

No.	Questionnaire Items (21 Degree Likert-type)	*Dimension*
1	How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?	*Mental Demand*
2	How much physical activity was required? Was the task easy or demanding, slack or strenuous?	*Physical Demand*
3	How much time pressure did you feel due to the pace at which the tasks or task elements occurred? Was the pace slow or rapid?	*Temporal Demand*
4	How successful were you in performing the task? How satisfied were you with your performance?	*Overall Performance*
5	How hard did you have to work (mentally and physically) to accomplish your level of performance?	*Effort*
6	How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?	*Frustration Level*

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