Experiences with a Virtual Reality System for Immersive Decision Making and Learning

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***Abstract*—A Computer Automated Virtual Environment (CAVE) can be used to set up immersive Virtual Reality (VR) setups of real-world applications in e.g., public safety, infrastructure prototyping, and education. These environments combine real-time motion tracking with high-resolution 3-dimensional projections onto four panels arranged to form a room-sized cube that enhances the users' immersive experience fostering interdisciplinary research and scientific applications. The CAVE system offers a novel and unmatched paradigm for cutting-edge VR research in comparison to conventional VR technology, such as Head-Mounted Displays (HMDs). However, its effectiveness and usability needs to be studied in the context of diverse applications. In this paper, we present a study of the "Mizzou CAVE" at the University of Missouri-Columbia, and report on the experiences in terms of its usefulness in cross-disciplinary applications, and the opportunities/challenges for potential researchers and users. Specifically, the study features Likert-scale-based questionnaires to collect empirical quantitative data for measuring efficacy and satisfaction outcomes striving towards the purpose of applications involving decision making and learning. Our survey findings obtained from CAVE users and content developers highlight the unique system capabilities of realism, customization, simplicity, interactibility, comfort, and potential for collaboration.**

***Index Terms*—immersive virtual environments, virtual reality, usability study, interdisciplinary collaboration, cybersickness**

I. INTRODUCTION

In recent years, immersive virtual environments have emerged as powerful tools for cutting-edge research in various fields, with the Computer Automated Virtual Environment (CAVE) being a prominent technology in numerous scientific investigations [1], [2]. The CAVE system provides a dynamic immersive virtual environment for setting up real-world application experiences. It has been utilized in various fields, including but not limited to entertainment [3], public safety training [4], disaster response [5], infrastructure prototyping [6], and education [7]. As such, it has become a valuable tool for new forms of research and teaching/learning [8].

The prominence of the CAVE in these several domains drives the need to investigate on its usability and applicability. With usability, the idea is to match the users and developers with their specific tasks and context of their execution [9]. There are several systems that are prevalent in the AR/VR space which can be assessed with these usability studies that allow the users to have the best experience in a simulation with little-to-no sense of cybersickness [10]. The evaluation and assessment of usability based on the experiences of users and developers is key to establishing that CAVE-like systems are not inherently perfect and one system might have superiority over the other based on their applicability [11], while one kind of system might also be more preferable for a specific application situation.

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In this paper, we detail the experiences of the "Mizzou CAVE" system located in the Cyber Education, Research and Infrastructure Center (CERI) at the University of Missouri-Columbia. The Mizzou CAVE has been a critical tool for interdisciplinary research collaborations across different domains, as shown in Figure 1. This paper highlights the essential features of the system that make it a premier virtual environment for investigating scientific applications in different disciplines [12]. In addition, it details experiences within immersive virtual environments in terms of effectiveness and usability for demonstrating the significance of the CAVE system as a state-of-the-art tool. Further, we highlight the unique features and potential of the CAVE system (e.g., in terms of sense of presence and immersion, ease of conducting research, body tracking, setup and calibration, and comfortable/no fatigue) for advancing research and discovery across multiple domains.

The goal of our study is to provide insights to help researchers effectively use VR and realistic application setups to develop new and improved experimental methods. We are also interested in understanding how educators can benefit from online learning platforms built with CAVE-based interactive tools to improve their teaching methods and help students learn more effectively [8]. We consider the use of emerging VR-related technologies [1] and compare CAVE and head-mounted display (HMD) systems that have different levels of cybersickness factors e.g., occurrence, symptoms and causes. Correspondingly, we report on the experiences of the Mizzou CAVE in terms of its usefulness in cross-disciplinary applications, and the opportunities/challenges for potential researchers/developers and users. Specifically, the study features Likert-scale-based questionnaires to collect empirical quantitative data for measuring efficacy and satisfaction outcomes striving towards the purpose of applications involving decision making and learning. Our survey findings obtained from CAVE

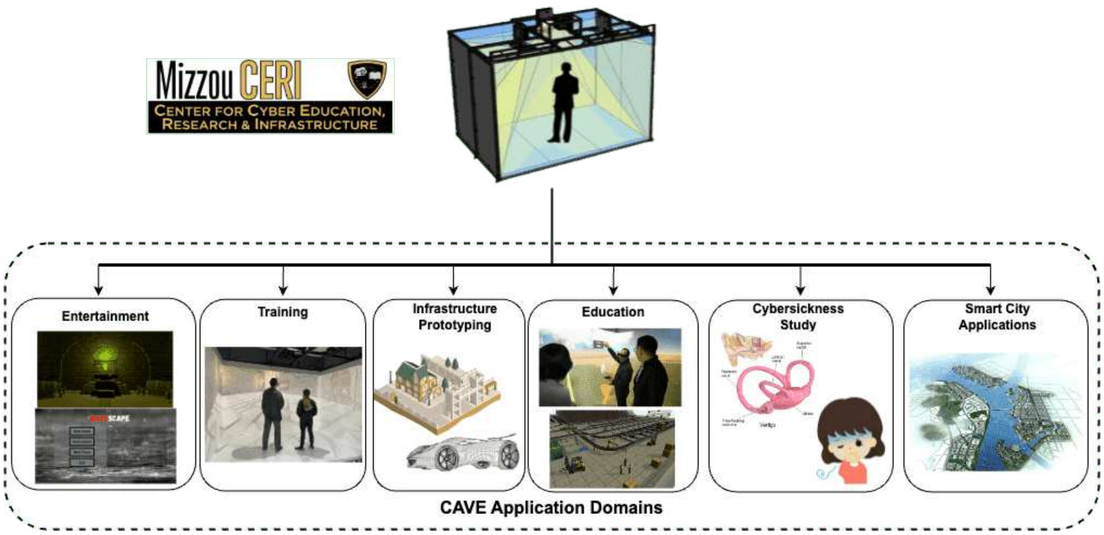

Fig. 1: Illustration of the Mizzou CAVE system and its cross-domain applications for immersive decision making and learning.

users and content developers highlight the unique system capabilities of realism, customization, simplicity, interactibility, comfort, and potential for collaboration.

The remainder of this paper is organized as follows: Section II provides an overview of the Mizzou CAVE system's configuration. Section III presents a detailed comparative analysis between the Head-Mounted-Display (HMD) and CAVE systems. Section IV presents the CAVE system applicability in various domains. Section V presents project case studies in the development of cross-domain CAVE-based applications. Section VI showcases the Mizzou CAVE usability evaluation based on surveys conducted on a group of users and developers to show salient findings on effectiveness and usability of the Mizzou CAVE, both qualitatively and quantitatively. Section VII concludes the paper.

II. Mizzou CAVE System Configuration

A. CAVE System Hardware

The VisCube M4 CAVE Immersive 3D Display used to build the Mizzou CAVE system has a resolution of 2560x1600 for the center and floor, and 1720x1600 for the sides. The image size for the center and floor is 140" x 87.5", and for the sides is 94" x 87.5". The footprint of the display is approximately 12.5'w x 8.3'd x 10'h. It includes a freestanding aluminum framework with a floor surface, rigid grey diffusion screen panels. The image generator of the system for the visual effects consists of a Dual Intel Xeon Gold 5122 (8 cores total), 192 GB RAM, 2 TB SSD, Blu-ray burner optical drive, and an Nvidia Quadro RTX6000 graphics card connected to a 2560x1440 32" console LCD monitor. The A.R.T. TrackPack4 is an optical tracking setup with 4 cameras that are wireless and employs one head tracker and one wand with a tracker. Other hardware parts added to the system are a second Nvidia Quadro RTX6000 GPU, an A.R.T. EGT4 target for Volfoni EDGE, and an A.R.T. Flystick2.

B. CAVE User Interface

The users can walk into the Mizzou CAVE system as shown in Figure 1 that provides an immersive experience. There are four WQXGA DLP projectors with 2400 lumens each with active stereo emitters that project high-resolution images and a stereo emitter featuring a soundbar and subwoofer with 4.1 channels that provides ambient sound. Users can wear Volfoni EDGE 3D glasses enabling several users to feel immersed in the environment, all at once. Also there is a leader for Volfoni EDGE glass that consists of the A.R.T EGT4 sensors. The A.R.T Flystick2 is a controller that allows the user to move around and interact with the objects in the simulation.

C. CAVE System Software

1) MiddleVR: MiddleVR [13] software is specially designed for multi-display, stereoscopy, high-performance rendering for VR systems such as the CAVEs. MiddleVR can handle all aspects of multi-display and high-performance rendering, and also adds VR capabilities such as: input devices, stereoscopy, and interactions. It offers a C# API (application programming interface), and a graphical user interface to configure a VR system.

2) Unity Engine: Unity is a cross-platform game engine that may be used to make 2D/3D, AR/VR, simulations, and other experiences [14], [15]. The engine's versatility extends beyond simple game production to areas like cinema, automobile, architectural designs, engineering, and constructions, as well as the United States Armed Forces. This Engine has a number of packages that support various computer vision applications as object identification, semantic segmentation, instance segmentation, and human-pose estimation.

3) Unreal Engine: A 3D computer graphics game engine called Unreal Engine (UE) was created by Epic Games and debuted in the 1998 first-person shooter game Unreal [16]. It was initially created for first-person shooter PC games, but it has since been adapted for usage in many different game genres and by other industries, most notably the film and television business. The C++-based Unreal Engine is highly portable and supports a variety of PC, mobile, console, and virtual reality platforms.

III. Comparative Analysis between HMD and CAVE

In this section, we provide a comparative analysis of HMD and CAVE systems, emphasizing their differences in virtual reality applications. Additionally, we present survey results from Mizzou CAVE users at the University of Missouri-Columbia, including an explanation of CAVE advantages.

A. Background

Head-mounted display (HMD) is a device that presents virtual reality directly in front of users eyes, disconnecting them from the real-world and allowing them to experience a virtual world. While Head-Mounted Display (HMD) devices are widely known for immersing users in virtual reality experiences, particularly in the gaming industry, they come with limitations when applied in professional and research settings. In contrast, CAVE systems were purpose-built to address these limitations and apply virtual reality technology to scientific and engineering domains [17].

Virtual reality has already gained immense popularity in entertainment, predominantly through HMD-based gaming, offering users experiences beyond the confines of the real world [18]. However, the potential for immersive experiences can be further elevated in a CAVE-based environment. CAVE technology extends beyond gaming, finding applications in sports, tourism, performance, exhibitions, and other entertainment domains where the sense of presence is crucial. Users can immerse themselves in scenarios such as spectating a sports event in a realistic stadium or engaging in sports activities that may be inaccessible due to physical limitations.

Distinctive factors, including display quality, user comfort, sense of presence, and collaborative possibilities, differentiate these two systems. A CAVE system provides a novel approach to virtual reality, addressing HMD limitations effectively. Its primary advantages include the ability to accommodate multiple users simultaneously, a broader field of view, and the opportunity for users to physically interact with the virtual environment [19].

Figure 2 shows the evaluation of CAVE users across seven categories: comfort, motion sickness tolerance, seamlessness, interactivity, intuitiveness, beginner-friendliness, and realism. The results overwhelmingly favor the CAVE, with the majority of respondents indicating strong agreement or agreement across all the seven categories.

B. Display

TABLE I: Comparison of display in HMD and CAVE [17]

Feature	HMD (Meta Oculus Rift)	CAVE
Resolution	1 Mpixel per eye	2-24+ Mpixels per screen
Image Quality	requires distortion and color correction	pixel perfect
Field of View	100 degrees	170 degrees

When evaluating immersive technologies, display features play a crucial role in shaping the quality of the virtual environment as shown in Table I. HMD and CAVE systems significantly differ in display resolution, image quality, and field of view, impacting the overall immersion. HMD products such as Meta Oculus Rift are limited in pixel density per eye, while CAVE displays offer higher pixel densities, ranging from approximately 2 million to 24 million pixels per screen. Thus, the CAVE displays provide a more life-like experience compared to general HMDs. Figure 2 reinforces this, with over 70 percent of respondents expressing strong agreement or agreement with the seamlessness of the CAVE display. Moreover, the difference in image quality makes CAVE particularly suitable for precision-dependent scientific applications, while HMDs are primarily used in gaming and entertainment. CAVE provides a 170-degree field of view (whereas HMD products only provide 100-degree field of view) resulting in a more realistic perception [18]. Given that human eyes have a horizontal field of view approximately 180 degrees [20], the field of view in CAVE is close to the actual human vision.

C. User Fatigue

One of the most significant factors that limits HMD in its wide use is visual fatigue [21]. Due to the short distance between the display screen and the eye, certain symptoms occur frequently to the users of HMD. Common symptoms accompanied by visual fatigue are eye strain, focus difficulty, general discomfort, nausea, and headache [21]. Even though the extent of symptoms may vary from user to user, it is apparent that they impose a severe restriction on its usage over an extended period of time. HMD products generally have all VR-related components compacted into the device, increasing its weight. For example, Meta Quest 2, one of the consumer-based products, weighs 503 grams which is heavier than common 3D glasses which weigh less than 100 grams. This can adversely cause neck and shoulder fatigue over time. On the contrary, CAVE utilizes a space rather than an integrated single device, allowing visual and physical fatigue to be substantially reduced in a CAVE setting. Moreover, CAVE only requires users to wear a lightweight 3-dimensional shutter glasses, which they can effectively use with relative comfort and efficiency for a prolonged period of time. As shown in Figure 2, in terms of Level of Comfort and Level of Motion Sickness-Free, the great majority of respondents answered Strongly agree or Agree for using the CAVE.

D. Sense of Presence

Sense of presence is a state of consciousness of being present within an immersive virtual environment [22], creating a sense of ”being there” in users' mind [18]. When wearing an HMD, users cannot perceive their physical body to be part of the virtual environment due to the limited view displayed on the compact screen. Although using avatars in the virtual world could be an option for HMD simulations, the problem is that the sense of presence cannot be fully replicated by such avatars in the virtual world. A true sense of immersion occurs when an environmental factor and sensory stimulation are in close interaction [23]. Users can physically be present

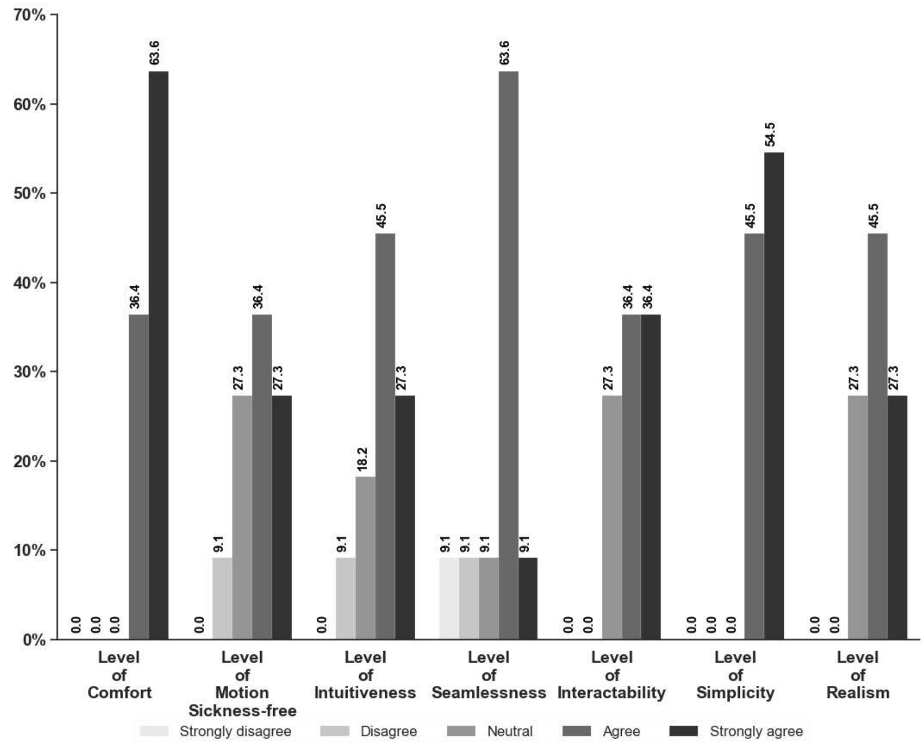

Fig. 2: User Experience in the Mizzou CAVE based on the Likert-scale survey for different categories

in the virtual setting of a CAVE, replicating the real-world movements. This is supported by Figure 2 showing that approximately 72 percent of the survey respondents answered either Strongly agree or Agree in the Level of Interactivity with Virtual Objects and the Level of Realism in a CAVE. Authors in [23] noted that the CAVE system was an ideal apparatus to study risk-compensation because it enables a higher sense of presence, allowing users to see both the physical and virtual worlds.

E. User Collaboration

A crucial requirement of spatial immersive platforms is to allow multiple simultaneous users [24]. Collaborative sense-making has long been recognized as one of the most valuable potential advantages of a CAVE [24]. While a CAVE is designed to provide collaborative experience along with physical affordances, HMD is centered around a personal use with limited physical movements [24]. User collaboration is critical in fields that require real-time interaction for collaborative tasks. On the other hand, a CAVE allows users to see others physically, creating a conducive environment for sharing thoughts on specific collaborative tasks and for interpreting nonverbal cues, which is essential for communication.

IV. CAVE Applications in Various Domains

The utilization and exploration of CAVE have been growing in a number of application domains and projects [2]. One of the goals for CAVE technology is to offer a virtual environment for user interface in such applications as entertainment, training, simulation, education, and many other areas of human activity [19]. The range of applications for CAVE is continuously expanding as it offers numerous powerful technical capabilities [2]. The following subsections suggest specific applications of CAVE in various domains which have the potential to lead to new discoveries and education/training.

A. Training and Education

CAVE can be utilized in various ways in the area of training for public safety. It can offer a risk-free environment to simulate hazardous on-the-job situations, enabling individuals to experience real-time consequences, learn from mistakes, and enhance their situational awareness [23]. For instance, the U.S. Army Research Laboratory developed an advanced VR system incorporating CAVE display and an Omni-Directional Treadmill to provide intensive training in hazardous military missions, supporting soldiers to experience immersive and realistic scenarios [23]. Also, first responders such as fire fighters can also benefit from training for urgent situations through CAVE. This can be cost-effective, for it does not require real equipment or facilities to be damaged or wasted while training. Preparing for future disasters is an essential part for public safety. Public can learn and train how to manage disastrous situations through CAVE. One effective method can be re-experiencing past disasters with a high sense of presence which can help maintain the awareness of the problem without diminishing the impact of the event [25]. CAVE can be used as a tool for group of individuals to learn and explore how to carry out a crisis situation. In 2007, Ericson utilized a CAVE virtual environment to teach children about rules of fire safety and to help them understand how to escape from fire situations, which is impossible to practice in real life [26] [23].

CAVE can provide visual graphics and auditory effects. While learning a certain concept, being actively involved in the relevant environment makes it easier to intuitively comprehend and learn the details of the concept. NICE project in 1998 is a good example of the early CAVE application in the educational field [27]–[29]. It aimed to create a learning environment on virtual ecosystem for children in an immersive and interactive feature [2]. CAVE can be utilized not only in learning environments, but also in various research areas. For instance, in the fields of astronomy and space science, it is impossible for students and researchers to experience the actual space. A CAVE system can be used to collaboratively analyze unique cosmic phenomena and simulate rarely known occurrences of the space. In addition, scientific visualization is an essential tool for learning in most of the natural sciences such as physics, chemistry, geology, meteorology etc. Novel ways of learning and conducting researches can be achieved via CAVE, leading to possibilities for new findings.

B. *Infrastructure Prototyping*

Prototyping is essential in product development; however, it can be time-consuming and costly to test its functionality once it has been created [6]. 3D models can shorten the period of development and also improve the quality through testing and simulating without a physical process in the design stage [6]. This applies not only to general products, but also to city infrastructures such as public building/facilities and transportation planning where function-specific prototyping can be embodied in full-scale by CAVE, obviating even the need for the cost involved in building the simplistic miniature structures. Testing and analyzing the efficiency of a prototype for a new railroad or new recreational park requires an enormous expense. It is also necessary to test whether the railroad will not harm the nearby ecosystem or whether the park is easily accessible to the public without causing traffic congestion near the area. CAVE can enhance the effective planning of city infrastructures by simulating different circumstances in real life, improving the feasibility and quality of urban projects.

V. Case Studies: Exploring CAVE System's Cross-Domain Applications

The Mizzou CAVE system has provided valuable functionalities to cross-domain applications, and has allowed researchers to explore new designs and concepts that would not have been otherwise possible without the CAVE capabilities. Additionally, the Mizzou CAVE system has resulted in unique data sets and simulations, providing researchers with new insights and advancements in their respective fields as shown in Figure 1. In this section, we highlight key projects in the form of application domain case studies with the Mizzou CAVE system that spans cross-cutting fields such as entertainment, public safety, infrastructure prototyping, and education.

Fig. 3: Developers testing the CAVE Escape prototype

Fig. 4: Treasure Room showcase in the CAVE Escape

A. *Case Study 1: CAVE Escape*

1) Project Overview: Even with the current boom in VR, there is still a significant lack of games that utilize VR technology. With gaming hardware and software generating \$130.0B annual revenue, it is alarming that VR only accounts for 0.4%. The CAVE Escape Room project illustrated in Figure 3 developed by students in a senior undergraduate capstone project seeks to put VR gaming on the map, through a VR escape room programmed entirely in Unity and configured into the CAVE using the MiddleVR library. The game was created to operate on the Mizzou CAVE system and players have to find their way through a series of puzzles to solve as they progress through each of the 4 rooms. As players advance through each room, the complexity and difficulty of the puzzles increase, offering a progressively more challenging experience. The game environment emulates game mechanics similar to those of physical escape rooms. The game's environment is filled with interactivity and utilizes the A.R.T Flystick2 joystick to the fullest. The game has ambient sounds, and allows the players to grab objects, carry them, and use them to solve the puzzles at hand. The players must use their surroundings along with some problem-solving skills and creativity to traverse the levels. Upon completion, the user is treated to a treasure room that is shown in Figure 4 to obtain rewards/spoils of victory.

2) CAVE Challenges: There were several challenges that the developers faced in the project. Firstly, the issues arose relating to the camera capabilities with a single motion detection glass, thus only allowing one user with control of the point-of-view that complicates the design of multiplayer scenarios. Another issue pointed out by the developers was related to the controller, where issues arose in terms of ergonomics and simplicity. Finally, a challenge that was discussed is the development of the game and the span of time they had to spend perfecting the games' graphical interface and audio setup that seamlessly creates a realistic immersive environment.

3) Advances/Lessons: The CAVE Escape Room project presents several research advances in the field of VR gaming. One of the most significant advances is that the project has brought forth the development of a novel Unity asset. This asset being an immersive environment allows users to interact with objects, solve puzzles, and integrates audio modulations. The project also highlights the significance of collaboration between students and faculty. Lastly, the project teaches lessons on the importance of problem-solving skills, creativity, and technical expertise needed for the development of VR games in a CAVE system.

B. Case Study 2: Meteorology Simulations

1) Project Overview: In the meteorology simulations project, the Mizzou CAVE system was used to create immersive 3D environments to help students gain a deeper understanding of mid-latitude cyclones as shown in Figure 5. The project consists of a multi-disciplinary collaboration of several experts with synergies in meteorology, AR/VR, and mixed reality. Firstly, the developers created an immersive and interactive learning environment with a navigable 3D VR model to emulate how air moves within mid-latitude cyclones including the abilities to control and manipulate the weather events by a user as shown in Figure 6. The interface allows access to standard media controls such as pause, play, fast forward, rewind, and skip, to enable users to control the weather event animations. Additionally, the application setup allows users to toggle between two layers of animation: an abstract view with basic geometric arrows and shapes that show wind behavior, and a realistic view with a detailed layer that mimics real-life weather events. Lastly, this fully immersive and interactive weather model was then presented to students enrolled in the 'Synoptic Meteorology II' course at the university to understand and research the benefits of new age e-learning models in contrast to conventional classroom lectures. The developers noted that this project advances the understanding of the students, eases the burden of the instructors to teach simulations of different weather events.

2) CAVE Challenges: The simulation of complex weather phenomena can be a challenge for the developers to mimic in the CAVE. One challenge that the project developers mentioned was their development of the related environments

Fig. 5: Showcase of Meteorology simulations to understand weather events

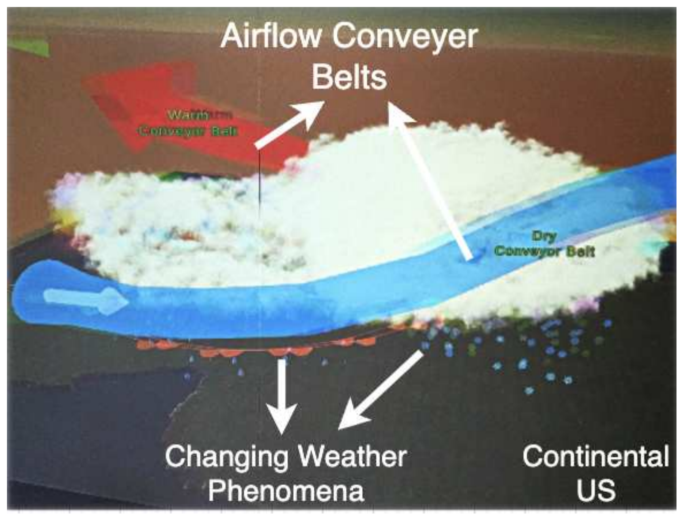

Fig. 6: Weather phenomena in the simulation.

was time-intensive, mainly due to the need to suitably decide and import the relevant assets that could be used in the environments. They also discussed that these environments required a physics playground to simulate what effect a certain type of weather should have on the objects in the environment. There is a need for developing assets that easily caters to the education requirements in meteorology and the complexity increases based on the size of the environment. For example, for a smaller space, it is relatively easy to detail the objects and their movements, however for a larger simulation space, the complexity increases exponentially.

3) Advances/Lessons: The meteorology simulation project presents several research advances in the field of simulation of different weather events. One of the most significant advances is that the project has brought forth the development of physics playground in Unity. This asset is an immersive environment that allows users to interact with different weather event conditions information with a real sense of presence. The project also highlights the significance of collaboration between students and faculty. Lastly, the project teaches lessons on the importance of dealing with the complex issues involved in weather models, creativity, and technical expertise needed for the development of realistic simulations of weather events in a CAVE system.

C. Case Study 3: Cybersickness Analysis

1) Project Overview: Cybersickness, a phenomenon characterized by symptoms like nausea and dizziness, is a prevalent occurrence in extended reality (XR) systems. However, the exploration of cybersickness in CAVE environments, as compared to HMD systems, remains limited [30]. Despite being universally experienced across all XR systems, there is a lack of standardized and comparable data collection between CAVE and HMD systems. To bridge this gap, an ongoing study with the Mizzou CAVE aims to implement the CSAssessmentFramework tool [31] shown in Figure 7 that was developed by Adriano Milani, enabling standardized and comparable data collection across different XR devices. The objective is to gain a better understanding of cybersickness, its causes, and potential differences and advantages between each system used. This research project has the potential to advance the field of XR and cybersickness research and facilitate the development of more comfortable immersive environments [32], [33].

2) CAVE Challenges: The utilization of the Mizzou CAVE system presents unique challenges in studying cybersickness. The requirement of shutter lenses, unlike HMDs, can cause discomfort for users, potentially leading to inaccurate sensor readings and affecting the overall data collection process [31], [34]. Moreover, the discomfort caused by shutter lenses can result in reduced immersion, which may produce skewed data regarding the cybersickness experience. Additionally, the CAVE system allows for more user movement, making it difficult to draw direct comparisons with other XR devices that involve limited or no movement. These challenges underscore the importance of developing specialized methodologies and techniques to ensure standardized and comparable data collection in CAVE environments. By addressing these challenges, the study aims to provide valuable insights via cybersickness analysis and contribute to the development of more safe-to-use VR environments.

3) Advances/Lessons: Cybersickness results from a sensory conflict between the visual cues received in the virtual environment and the body's vestibular system, which senses motion and balance. Studying this phenomena can help make informed strategies for mitigating cybersickness. The framework aids in understanding locomotion methods, visual cybersickness reduction techniques, customizable experiment settings, and a centralized interface. Researchers can easily manipulate content factors and assess their impact on cybersickness. The CSAssessmentFramework tool also enables real-time data logging, making it possible to capture user head movement and physiological signals for analysis. The framework's preset system allows for easy sharing of experiment presets among researchers, enhancing replicability and collaboration in the field. With its focus on cybersickness-specific features, CSAssessmentFramework tool contributes to advancing our understanding of cybersickness and improving the efficacy of VR experiences.

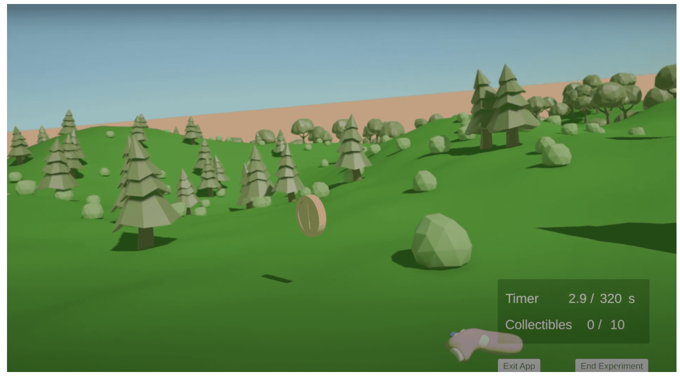

Fig. 7: Cybersickness Assessment Framework environment

D. Case Study 4: Visualizing City Scale 3D Meshes

1) Project Overview: The project aims to explore the use of immersive virtual environments, specifically the CAVE, for scientific applications such as urban planning, architecture, civil engineering, and transportation engineering. The project's goal is to utilize the capabilities of mixed reality and 3D modeling to display city meshes in mixed reality devices such as the Mizzou CAVE [35]. The project used the Unity Game Engine to create real-world accurate meshes by creating dense 3D point clouds of urban areas in Columbia, MO and Albuquerque, NM. Additionally, the project's mesh generation and texture mapping methods can help transportation engineers understand traffic flow patterns and design safer roads [35]. The experimenters studied how to produce 3D visualizations by doing a comparative analysis of 4 meshing algorithms: ball-pivoting, greedy triangulation, Poisson reconstruction, and screened Poisson reconstruction [36].

2) CAVE Challenges: The implementation of the immersive virtual environment for creating city scale 3D meshes created several challenges. One of the major challenges in this project was the generation of realistic and accurate meshes for virtual environments as shown in Figure 8, which can be caused by the high computational resources needed as well as the advanced techniques for texture mapping. An additional challenge faced by the developers related to the building of an accurate, lag-free, and realistic user interface that can interact with the virtual environment. In addition, creating a 3D model of a city to be viewed in a CAVE is difficult because of problems such as e.g., not having enough data, noise, and missing information.

3) Advances/Lessons: Despite these challenges, recent research has shown significant advances in the use of immersive virtual environments such as the CAVE. For example, the visualization of real-world accurate meshes in virtual environments using Unity Game Engine has provided a valuable tool for architects and urban planners to better understand how a building or a new development project would fit into a surrounding cityscape [35], [36]. Additionally, the use of CAVEs for drone flight planning and aircraft training has assisted in training pilots and in the development of autonomous vehicles [37]. The experimenters also made a custom process to use their data to create a more immersive experience, with detailed models and custom textures [36].

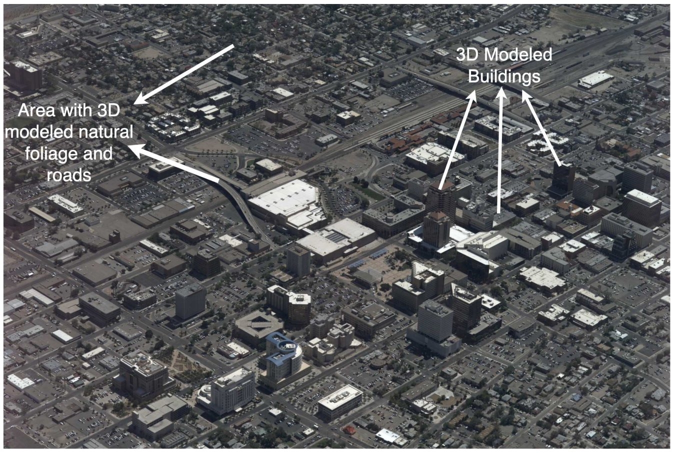

Fig. 8: CAVE environment with 3D model of Albuquerque

Fig. 9: University of Missouri Campus rendered on CAVE using a meshing algorithm

E. Case Study 5: Multi-modal 3D Modeling of Cities

1) Project Overview: Another project that is similar to the one in Case Study 4 was carried out with the focus on a workflow for creating real-world accurate synthetic environments that can be visualized in the CAVE. The workflow involves converting point clouds into polygon meshes, applying photorealistic texture mapping, and transferring the meshes into Unity to create synthetic environments for visualization as shown in Figure 9 and drone flight planning experiments [36]–[38]. The MiddleVR and UniCAVE plugins enable the distribution of Unity applications to the CAVE and allow for interaction using the CAVE's wand or a game controller. The final output is a realistic, textured 3D model that can be used for various purposes, including virtual tours and simulations. Specifically, the University of Missouri campus was rendered in the Mizzou CAVE for such related purposes. Without the CAVE, it would not be possible to fully immerse oneself in these synthetic environments and explore them in a way that closely mimics reality.

2) CAVE Challenges: One of the main challenges of creating realistic synthetic environments for the CAVE is achieving high levels of visual fidelity. The CAVE offers an immersive experience, and any imperfections or inaccuracies in the environment can be immediately noticeable and jarring to the user. Additionally, creating a workflow that is both efficient and effective is a challenge, as there are multiple steps involved in converting point clouds into polygon meshes and applying texture mapping. Finally, ensuring that the synthetic environment is accurate to the real-world environment can be a challenge, as there may be limitations in the accuracy of the data collected in the point cloud.

3) Advances/Lessons: Despite the challenges, the development of the workflow and the use of the CAVE for visualizing synthetic environments have led to several advances and lessons. For example, the workflow has shown the potential for using the CAVE for urban planning and simulation, allowing users to experience and explore different scenarios in a more immersive and interactive way. The use of photorealistic texture mapping has also improved the realism of the synthetic environments and allowed for a more accurate representation of the real-world. The project has also highlighted the importance of data quality and processing algorithms for creating accurate and realistic synthetic environments.

F. Case Study 6: MazEscape Game

1) Project Overview: MazEscape is a project that involves game development and fostering a collaborative environment in a VR space. Similar to the approach in Case Study 1, the developers created an exit generated at run-time that ensures the environment is randomized. Users meet obstacles and resistances along the way appearing at timed intervals. User can interact with objects in the environment to fend off, in case they are obstacles.

2) CAVE Challenges: The requirements of the project varied in terms of the type of hardware needed, rendering applications, tracking and interactivity devices, synchronous development tasks and keeping these hardware devices and software requirements ready for execution. The team did not face any notable challenges in terms of satisfying the requirements presented for the project. However, many of the developmental tasks were time-consuming because they required development of different aspects of the game development such as e.g., asset creation, rendering it in game engines, and configurations of the motion tracking sensors.

3) Advances/Lessons: The MazEscape project presents several research advances in the field of VR gaming. One of the most significant advances is that the project has brought forth the development of a novel Unity asset. This asset is an

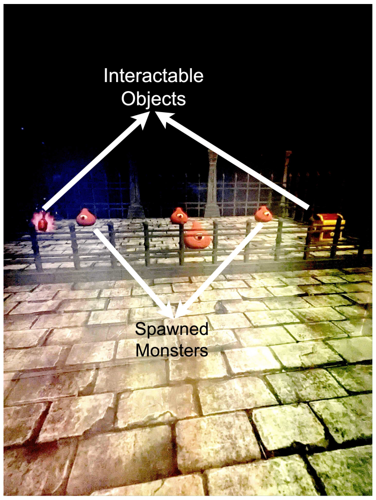

Fig. 10: MazEscape visual sample from the Mizzou CAVE

exemplar for any development related to environments that are created in run-time that defy the preset environments. The project also highlights the significance of collaboration between students and faculty. Lastly, the project teaches lessons on the importance of keeping track of path traversals to complete a timed task, and the use of motion sensors/trackers to give immersiveness that makes the game playing enjoyable to the users.

VI. Usability Evaluation

In this section, we detail the usability study that was performed to assess the experiences of two focus groups. Focus Group I consisted of the general users in the CAVE and Focus Group II consists of the developers that are actively engaging in developing these simulations using VR prototypes. The information about the experiences of both the focus groups was conducted using a Likert scale survey. Based on informed consent obtained following the Institutional Review Board (IRB) guidelines, 10 users in Focus Group I and 7 developers in Focus Group II were recruited as participants, and were engaged in an online survey to provide their remarks about several usage paradigms of the Mizzou CAVE.

A. Focus Group I

The results of the Likert scale survey conducted during Focus Group I provide valuable insights into the usability of the CAVE system. Participants were asked to rate their levels of agreement or disagreement regarding various variables related to usability. The survey encompassed several key aspects, including comfort, motion sickness prevention, intuitiveness, seamlessness, interactability, simplicity, and realism.

1) Level of Comfort: Participants were asked to rate their comfort level while using the CAVE system. The majority of participants (63.64%) strongly agreed that the system provided a high level of comfort. This indicates that the CAVE system offers a comfortable user experience, which is crucial for prolonged usage without discomfort or fatigue.

2) Level of Motion Sickness-Free: The survey assessed participants' perception of the system's effectiveness in preventing motion sickness. A significant portion of participants (36.36%) agreed that the system successfully reduced the occurrence of motion sickness. This finding suggests that the CAVE system incorporates features or design elements that mitigate motion sickness symptoms, improving the overall user experience.

3) Level of Intuitiveness: Participants were asked to evaluate the intuitiveness of the CAVE system, focusing on its ease of use and understanding. The results indicated that a substantial number of participants (45.45%) agreed that the system was intuitive. This implies that the CAVE system offers a user-friendly interface and interaction design, enabling users to navigate and engage with the virtual environment effortlessly.

4) Level of Seamlessness: The survey aimed to assess the seamlessness of the CAVE system, which pertains to the smoothness of interactions and transitions within the virtual environment. The findings revealed that a majority of participants (63.64%) agreed that the system provided a seamless experience. This suggests that the CAVE system successfully integrates various elements, such as graphics, audio, and interaction mechanics, to create a cohesive and immersive user experience.

5) Level of Interactability: Participants were asked to rate the level of interactability offered by the CAVE system, emphasizing the ease and effectiveness of user interactions. A considerable proportion of participants (36.36%) strongly agreed that the system offered a high level of interactability. This implies that the CAVE system allows users to engage with the virtual environment in a responsive and interactive manner, enhancing the sense of presence and agency.

6) Level of Simplicity: The survey assessed participants' perception of the system's simplicity, encompassing ease of use and understanding. The results demonstrated that a majority of participants (54.55%) strongly agreed that the system was simple to use. This suggests that the CAVE system features an intuitive and straightforward design, allowing users to quickly grasp its functionalities and navigate through the virtual environment with ease.

7) Level of Realism: Participants were asked to rate the realism of the CAVE system, reflecting the extent to which the virtual environment appeared realistic. The findings revealed that participants (45.45%) agreed that the system provided a realistic experience. This indicates that the CAVE system successfully incorporates visual and auditory elements that create an immersive and believable virtual environment.

Overall, the survey results indicate positive evaluations of the CAVE system's usability across various dimensions. The high percentages of agreement and strong agreement highlight the system's effectiveness in providing comfort, reducing motion sickness, intuitive interaction, seamless experiences, high interactability, simplicity, and realism. These findings emphasize the system's potential for fostering user satisfaction

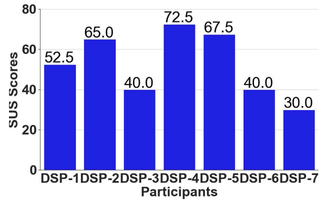

Fig. 11: Individual SUS Scores

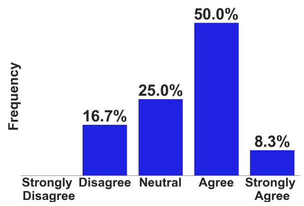

Fig. 12: CAVE Use Simplicity

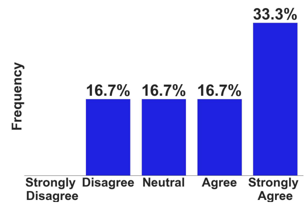

Fig. 13: Interdisciplinary Research Capability

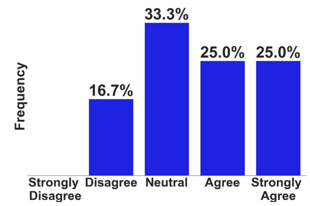

Fig. 14: Unique Features for Application Development

and positive user experiences, contributing to the overall success of the Mizzou CAVE system utility.

B. Focus Group II

In Focus Group II, the participants were asked to rate their levels of agreement or disagreement regarding various usability variables using a Likert scale. The System Usability Scale (SUS) [39] was used as a metric for the participants to show the overall user-friendliness of the CAVE system. Quantitative results indicated an overall SUS score of 52.5 on a scale of 100 (where 100 is the highest). The developers graded the CAVE system as "D/Marginal" on a scale of A to F, where A is the best in Figure 11. The inference from these usability study suggests that there are positive remarks from some of the users while others find it neutral on other aspects. The larger issue with the grade related to the need for more developer training materials and lack of access to a more rich assets marketplace to pursue new developments.

The CAVE system was positively perceived in terms of creating a sense of presence and immersion. The majority of participants agreed that the system effectively engendered a feeling of being present in the virtual environment, enhancing the overall immersive experience. Participants found the CAVE system to be relatively easy to use when conducting research as shown in Figure 12. A significant proportion either had a neutral stance or strongly agreed that the system facilitated research activities, indicating its user-friendly nature. The CAVE system's body tracking capabilities were well-received by the participants. A considerable number of participants found the body tracking to be satisfactory, indicating that the system accurately captured and translated their physical movements into the virtual environment. Participants expressed overall satisfaction with the setup and calibration process of the CAVE system. Many of them either had a neutral stance or agreed that the system was easy to set up and calibrate, contributing to a seamless and hassle-free user experience.

The majority of participants strongly disagreed (54.55%) with the statement that the CAVE system encountered technical problems during usage. This feedback suggests that the system performed well in terms of technical reliability and stability, indicating a positive user experience. The CAVE system received further positive feedback regarding comfort and the absence of user fatigue. A substantial number of participants agreed or strongly agreed that the system provided a comfortable experience, ensuring extended usage without discomfort. Participants expressed varying opinions about the system's support for collaborative research. While a significant proportion had a neutral stance, many participants agreed or strongly agreed that the CAVE system facilitated collaborative research efforts, as depicted in the Figure 13 promoting collaboration and knowledge sharing among users. The quality of research conducted using the CAVE system was positively evaluated by participants. A considerable number of participants agreed or strongly agreed that the system contributed to the production of high-quality research outcomes, underscoring its unique features and value in scientific-research based applications as shown in the Figure 14.

VII. Conclusion

In this paper, we present an in-depth discussion of the related theory, system configuration, hardware, and software of the Mizzou CAVE system, which can be used to setup cutting-edge virtual reality environments for cross-domain applications. Three major conclusions emerged from the study: The CAVE offers a more immersive experience with less user fatigue, a stronger sensation of presence, and multi-user cooperation than HMD does. Second, the special qualities of the CAVE can be used in a variety of contexts, including entertainment, training, infrastructure prototyping, and education. Third, by displaying its real-world applicability and contributions to furthering research and development in many application domains, the Mizzou's CAVE initiatives have illustrated the great potential of this system for gaining innovative perspectives and education/training in related application domains. Thus, the above conclusions highlight the Mizzou CAVE's importance as a promising virtual reality cyberinfrastructure that fosters future breakthroughs in cross-domain applications.

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