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Developing an Interactive VR CAVE for Immersive Shared Gaming Experiences

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Abstract: The popularity of VR technology has led to the development of public VR setups in entertainment venues, museums, and exhibitions. Interactive VR CAVEs can create compelling gaming experiences for both players and the spectators, with a strong sense of presence and emotional engagement. This paper presents the design and development processes of a VR interactive environment called MobiCave (in room-scale size), that uses motion-tracking systems for an immersive experience. A user study was conducted in the MobiCave, aimed to gather feedback regarding their experience with a demo game. The study researched factors such as immersion, presence, flow, perceived usability, and motivation regarding players and the bystanders. Results showed promising findings for both fun and learning purposes while the experience was found highly immersive. This study suggests that interactive VR setups for public usage could be a motivating opportunity for creating new forms of social interaction and collaboration in gaming.

Keywords: public VR; interactive CAVE; environmental VR; immersive gaming

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1. Introduction

Virtual Reality (VR) technology has become increasingly popular in recent years, and as a result, there are now a variety of VR setups that are designed for public usage [1–3]. These setups are typically found in entertainment venues, such as museums, exhibitions, and amusement parks, and allow users to experience immersive virtual environments in a shared setting [3]. In addition, the use of VR technology in public spaces can provide a way for organizations and educational institutes to communicate important messages and raise awareness about specific issues. For example, in [4], a VR game is used to raise awareness in children about endangered species by allowing players to see the impact that human behavior has on the *Caretta caretta* sea turtles in Greece; this setup enables users and bystanders to immerse themselves in a motivating way. Moreover, the entertainment industry can use VR CAVEs to create interactive experiences for users, such as virtual theme park rides or immersive video games [5]. Virtual environments with immersive games have the potential to be a powerful tool for educating children and young adults [6]. They can contribute to increasing awareness of and educating the next generation on crucial issues and topics by offering an immersive and engaging learning experience.

According to previous research, social elements such as other players or fictional characters can significantly affect a player's experience and sense of immersion in VR games [7]. Research has also examined the classification and relationships between VR and CAVEs, emphasizing the potential for both technologies to produce immersive experiences [5]. Kim et al. [8] examined the effects of telepresence via VR on consumer behavior and marketing strategies. Their findings indicate that VR experiences can create a strong sense of presence and emotional engagement, which could be harnessed to create compelling shared gaming experiences. In addition, multi-user setups can allow several people to play together in a virtual environment. Weech and Kenny [9] provided a philosophical exploration of the concepts of presence and absence in mixed reality, highlighting the potential of mixed reality experiences to create novel and engaging forms of shared gaming experiences.

Moreover, VR gaming experiences are researched for changes in interpersonal interactions. Players that are engaged in more complex and varied social interactions in VR compared to traditional gaming improve their user experience by increasing realism, engagement, and motivation [10]. A room-sized VR setup that provides an interactive experience for both users and the viewers can create more socially engaging gaming experiences. Menin et al. [11] point out the effects of using immersive VR technology combined with game aspects. Their work highlights the technical challenges involved in creating interactive VR and the importance of careful design and testing to create engaging and immersive experiences. VR games that are made in interactive builds create the possibility of a sense of place by incorporating the possibility of embodiment and presence into the design of control and movement, while ported VR games fail to reach this level of immersion because of a lack of technological intentionality towards these goals [12].

Previous studies have examined how users behave and how they interact with immersive VR environments, as well as how the features of VR systems affect users' intents to utilize them for particular purposes, such as wayfinding behavior in multi-level buildings [13], scale estimation for design decisions in virtual environments [14], and the dimensions determining telepresence [15]. Additionally, VR has been explored in the context of the built environment, with research focusing on applications of VR for indoor navigation [16], human wayfinding performance using vertical and horizontal signage [17], and research trends and opportunities in the field [18]. The effect of user attributes on spatial perception and design choices in immersive VR systems is one area of VR that has been studied. The significance of spatial perception imperatives in VR and how view usage patterns affect spatial design decisions were also examined by Azarby and Rice [14]. Similar to this, Leyrer et al. [19] looked at how crucial postural cues are for establishing eye height in immersive VR.

In the context of gaming, VR has been found to enhance learning, emotions, and problem-solving behaviors when users have a high level of agency [20]. Moreover, immersive VR systems can create compelling gaming experiences for both players and spectators, with a strong sense of presence and emotional engagement [21]. Allman et al. [22] (p. 360) explored the perception of additional information content in 360° 3D VR video for teaching and learning purposes. VR systems have significant potential for enhancing user experiences and behavior in various fields, including gaming. However, more research is needed to understand the full range of capabilities and limitations of VR systems and how they impact user behavior and experience in different contexts. This study presents the design and development of an interactive VR environment for shared gaming experiences. In particular, the efforts in developing a custom VR technology interactive environment are presented. The interactive VR CAVE is built in room-scale size and uses motion-tracking systems to allow users to physically walk around in the virtual environment and provide an immersive experience. Players use their body for interaction and the final setup is tested through a gaming environment with university students. Results show promising findings for both fun and learning purposes of the interactive VR CAVE. This kind of VR technology can offer a real immersive environment for users (players) and for bystanders. Our work suggests that interactive VR setups for public usage could help to create new forms of social interaction and collaboration in gaming.

The rest of this paper is structured as follows: In the second section we research background work regarding public VR experiences and motion capture in VR. Next, we present the process followed for creating MobiCave. The fourth section reports on the user study that we conducted to test this setup within a gaming environment. This is followed by a discussion, in the fifth section, highlighting challenges and opportunities for enjoyment, for learning purposes, and for the bystanders. Finally, the sixth section concludes this article with possible future work.

2. Related Work

2.1. Factors Affecting User Experience in Virtual Environments

The user's experience (UX) and the sense of presence in a virtual environment is influenced by various factors that can affect their experience and behavior within that environment. These factors include the level of immersion, type of interaction with virtual objects, perception of spatial factors, and the way users shift between egocentric and exocentric viewpoints. Understanding these factors can help designers and developers create more effective and engaging virtual environments.

The level of immersion is one of the most crucial factors, which refers to the extent to which the virtual environment simulates the real world. The immersive capability of virtual environments can be manipulated to create different levels of immersion including low, moderate, and high [23]. Immersion impacts various factors such as spatial learning and training transfer [24]. In a non-immersive virtual environment, the user interacts with the virtual world through a two-dimensional screen, such as a computer monitor. In a semi-immersive virtual environment [25], the user is surrounded by a screen or projection system, which provides a partial sense of immersion. In contrast, a fully-immersive virtual environment [26] involves a complete immersion of the user's senses, including sight, sound, and touch. Presence in VR can trigger emotions such as excitement or discomfort, which can affect UX [27].

Another critical factor affecting user experience in VR is the type of interaction with virtual objects. In direct interaction, users manipulate objects within the virtual environment with their hands and it has been found to increase presence [28] compared to indirect interaction, where users manipulate virtual objects through a mouse or keyboard. Moreover, perception of the spatial factors of the virtual environment on a human scale is also a significant factor that impacts presence [29]. Users' ability to perceive the size, distance, and layout of virtual objects and the environment itself affects their sense of presence within the virtual environment [30]. View usage patterns and the way that a user shifts between egocentric and exocentric viewpoints also influence presence [31]. Egocentric viewpoints are those in which the user perceives the virtual environment from their own point of view, whereas exocentric viewpoints are those in which the user views the environment from an external perspective. The influence of avatars on the sensation of presence in room-mounted virtual environments has also been studied [32]. Effective use of both viewpoints can enhance the user's sense of presence within the virtual environment.

Finally, age and gender can also affect presence, user experience, and usability in VR [33]. A study involving 57 participants in VR found that older participants had a higher sense of presence than younger participants [34]. However, there were no gender differences or interaction effects of age and gender. The reported presence of individuals through presence questionnaires is the result of a cognitive judgment from the immersiveness, interactivity, and emotional arousal from the perceived content of the VR scenario [27]. Designing VR experiences for different age and gender groups requires a better understanding of how age and gender affect presence, user experience, and usability in VR. For example, a pilot study exploring age differences in presence found that older adults preferred a slower pace and more explicit instructions in VR [35]. Another study shows that older adults may have reduced visual acuity and hearing, which can affect their ability to interact with VR environments [36]. VR developers can consider the familiarity of different age groups with technology and adjust the level of complexity of VR experiences accordingly.

2.2. Public VR Experiences

Public VR experiences are immersive environments designed to be shared by many people in public spaces. They can be used for entertainment, education, training, or other purposes. A widely known case of VR setups in physical size are CAVEs [37]. A CAVE is a cube (typically room-sized) with walls that display 3D images, where the user wears stereoscopic glasses to experience a sense of depth [38]. The user's position and orientation are usually tracked and used to update the display in real time, providing a high level of interactivity and immersion. CAVEs are a challenge to design and construct because their numerous components are largely derived from pre-existing technologies that were originally created for different purposes [39]. The integration of these components and the building of certain critical custom parts such as screens and graphics cards involve years of research and development. CAVE2 is another example that combines a large-scale immersive display with VR and AR technologies in a hybrid reality environment [40]. It allows users to interact with 2D and 3D content using natural gestures and movements and supports collaboration among multiple users in the same virtual space. Related to this is KAVE, a Kinect-based automatic virtual environment that allows users to interact with virtual objects using natural body movements and gestures [41]. Furthermore, StarCAVE [39] is a third-generation CAVE. It is a 5-wall plus floor projected VR room, distributed over 15 rear-projected wall screens and 2 down-projected floor screens that provide a walk-in display.

Table 1 presents various VR systems, including immersive HMD solutions such as Oculus Quest 2 and high-end CAVE systems such as CAVE2. The table includes information on the field of view, display resolution, tracking technology, and other key characteristics of each system.

Table 1. VR system characteristics.

VR System	Screen Resolution	Number of Projectors—Panels	Field of View	Users
Immersive HMD (e.g., Oculus Quest 2)	1832 × 1920 per eye	N/A	~110°	1
CAVE2	4096 × 3072 per screen (×72 screens)	72 LCD panels	320° horizontal, 135° vertical	Multiple
CAVE1	1280 × 1024 per screen (×3 screens)	3 projectors	180° horizontal, 90° vertical	Multiple
Powerwall	4096 × 2160	1–4	180° horizontal, 60° vertical	Multiple
Tiled display wall	1920 × 1080 per tile (×multiple tiles)	Multiple	Dependent on configuration	Multiple

Researchers have explored the potential of social VR to create public spaces for people to interact with each other and with digital content. Eghbali et al. [42] examined experiential factors for the users and the bystanders for socially acceptable VR and created a set of design recommendations. In [43], collaborators gather together in front of a large-scale display to share research findings and utilize a multitouch digital whiteboard to brainstorm the next steps to advance their work. CAVEs also present benefits as immersive technologies for education. A study conducted by Back et al. [44] is a concrete example of the effective design and implementation of VR CAVE sets demonstrating learning gains to the more pervasive use of immersive technologies for education. The ability to share VR experiences with others can enhance the overall VR experience and make it more accessible to a wider audience. In [45], the effect of surfaces and spaces on visualization tasks performed by groups collaborating in a room-sized immersive environment was researched. Participants were given flexible visualization authoring tools to allow control in how they structure their shared workspace and the study observed novel behaviors that are unique to collaborative immersive analytics.

Several previous works focus on guidelines for creating public VR installations that are designed to be engaging and accessible for a wide range of users. Leeuwen et al. discuss in their study [46] the challenges of designing public VR experiences, such as addressing issues of accessibility, safety, and social norms. Related, in [47], Gonçalves et al. consider a low-cost VR surround-screen projection system. They evaluate both objective (e.g., head position estimation accuracy and precision) and subjective characteristics (e.g., sense of presence and cybersickness) of their CAVE-like system compared to advanced setups and HMDs. Additionally, Kalantari and Neo provide in their survey [48] an overview of the techniques and applications of social VR, including its potential use in public spaces. The authors discuss the challenges of designing VR experiences and provide a set of design principles and guidelines for creating successful installations. Another example is a museum installation called the Virtual House of Medusa [49]. The setup enables museum guides to support a VR interaction and to present the installation to a large audience. Authors argue that the interaction between the VR museum guide, the VR player, and the spectators has the potential to create a unique experience. Finally, Gonçalves and Bermúdez [41] discuss technical challenges of building the KAVE system, including the use of multiple sensors for tracking and the calibration of the virtual environment.

2.3. Motion Capture in VR

Motion capture in VR is a technique used to capture the movements of a person and track their body movements in real time. This technology has revolutionized the way people interact with virtual environments and has opened new possibilities for immersive experiences. Motion capture employs skeleton tracking which works by using cameras, sensors, or other types of tracking systems to detect the movements of the user's body [50]. These movements are then translated into the virtual environment, allowing the VR user to perform actions such as reaching, grabbing, and even walking. Motion capture can include the following:

- Full-body tracking, which involves tracking the position and orientation of the user's head, hands, feet, and other body parts to control the character's movements within the game [51].
- Hand tracking, which involves tracking the movement of a user's hands to control in-game actions [52]. This can include grabbing and manipulating objects, throwing projectiles, or performing hand gestures to trigger special abilities.
- Body posture and gesture recognition [53]. Some games use skeleton tracking to recognize specific body postures or gestures, such as a punch or a kick, to trigger in-game actions. This can provide a more intuitive and immersive gameplay experience, allowing the user to feel more connected to their character.

There are several technologies that can be used for skeleton tracking in VR, including:

- Inertial measurement units (IMUs) [54]: IMUs are sensors that measure acceleration, rotation, and magnetic fields. They can be attached to different parts of the body, such as the hands, feet, and torso, to track movement.
- Depth-sensing cameras [55]: cameras that use depth-sensing technology, such as the Microsoft Kinect or Intel RealSense, can be used to track the movement of a user's body.
- Optical motion capture [56]: This technology uses markers placed on a person's body and cameras to track their movement. This is commonly used in film and video game production. Once the user's movements have been tracked, the data can be used to animate an avatar in the virtual environment. This allows the user to see their movements reflected in the VR world, creating a more immersive experience.

Motion capture in VR has a wide range of applications, from gaming and entertainment to training and simulation. In [57], it is used to create a more realistic sports simulation for a table tennis game by tracking the player's hand movements and replicating them in the game. In the rhythm game "Beat Saber" it traces the player's hand movements as they slash through virtual blocks with laser swords [58], thus providing a more natural and immersive experience. Using motion capture, the player can move objects or navigate in the virtual world using their own body gestures and movements, without the need for a conventional handheld controller, which provides a greater sense of presence within the virtual environment; an example is the "Raw Data" game where the built-in motion capture algorithms track gamers' body movements and transform them into VR to shoot the enemies ("Raw Data" game on STEAM platform. Available online https://store.steampowered.com/app/436320/Raw_Data/ (accessed on 7 March 2023)). In education and training, skeleton tracking can be used to simulate real-world scenarios, such as medical procedures or hazardous environments, allowing the user to practice and learn in a safe and controlled environment.

Moeslund and Granum [59] provide an overview of motion capture technology and its applications in computer vision-based human motion capture. Their work discusses the challenges of implementing motion capture and some of the potential solutions. Related, Beddiar et al. [60] provide a comprehensive review of the current state of motion capture technology for human activity recognition (HAR) systems. They discuss the various approaches to motion capture (with markers and markerless) and compare their strengths and weaknesses. A paper by Banks et al. [61] presents a novel approach to motion capture in VR using a Vive Tracker. The system can capture full-body movements in real time and can be used for a variety of applications, including gaming and virtual training. A recent research study [62] describes a markerless motion capture system that uses the Microsoft Kinect Azure sensor to track the movements of a person in VR for sports rehabilitation of martial arts athletes. The system can capture full-body movements and could be a promising technology to monitor martial arts athletes after injuries to support the restoration of their movements and position to rejoin official competitions.

Overall, the use of motion tracking in VR is an important aspect of creating more immersive and interactive experiences for users. Especially in gaming, whether one is playing a VR shooter, a puzzle game, or any other type of VR game, skeleton tracking can provide a more exciting and engaging gaming experience.

3. Implementing MobiCave

The MobiCave VR environment is a simplified implementation of a CAVE system. The system consists of three walls and a floor projection, and the users do not wear stereo glasses. Head tracking is not used to change the content on the walls and the users' movement does not affect the content being viewed. MobiCave can support 3D projection by employing the anaglyph technique, as described in Zone [63]. This technique involves using colored filters to separate the left and right eye images and create a 3D effect when viewed through glasses with complementary filters. While anaglyph projection may not offer the same level of realism as other 3D display technologies, it can still provide a useful tool for visualizing 3D data in a cost-effective manner. We followed a three-part process to implement the MobiCave environment for immersive shared gaming experiences (Figure 1).

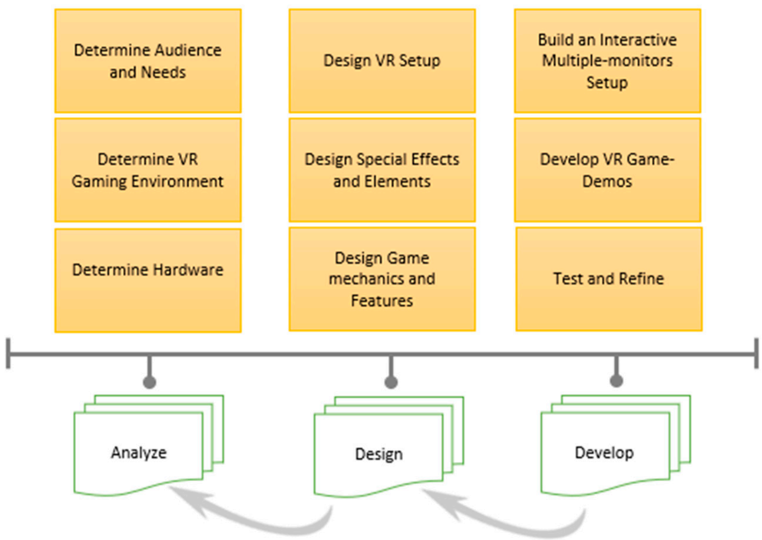

Figure 1. Process for the development of the MobiCave.

In the first part, we determined the scope of the project and identified the features that the VR CAVE should have and how it will enhance the gaming experience. We considered issues such as possible users, the size of the CAVE, the type of games it will support, the number of players, etc. Moreover, we determined the special VR needs for this setup to be used as a gaming environment. Then we had to choose the right hardware. We determined the number of monitors to use, their size, and the type of games we wanted to develop and play. We considered factors such as cost, compatibility, and performance.

In the second phase, we designed the VR setup that players will be immersed in (Figure 2). This included the layout and design of the CAVE, as well as any special effects or elements to enhance the experience. The design process involved scenarios with multiple monitors for a smooth VR gaming experience. We had to appropriately choose the system graphics card that can support multiple monitors, as well as any other necessary hardware such as cables, adapters, and mounting brackets. Moreover, in this phase, we had to consider some game mechanics and features such as skeleton and motion tracking for the games that will be developed for our setup. The basic design goals for the MobiCave were the following:

- Scalability, so it can fit a room-sized space.
- Usability, in normal room conditions, e.g., lighting.
- Multiplayer, to allow collaboration.
- Sharable, to allow bystanders to view fully and in this way to be part of the experience.
- Interconnected, easily transferable setup and rapid installation/de-installation for field and traveling exhibit use.
- Easy access for maintenance, to reduce expenses.
- Power-efficient, to reduce cost and cooling and low thermal signature to minimize need for ventilation.
- Low noise signature, so that the users and the bystanders can talk, and generated audio can be heard.
- Safety, in terms of construction and electricity, to prevent accidents, injuries, or damage to equipment.

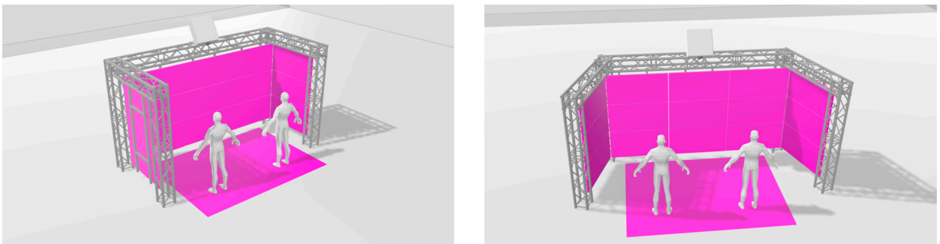

Figure 2. The MobiCave possible placements (**left**, 90 degrees; **right**, 120 degrees).

In the third phase, we constructed the VR CAVE environment. The MobiCave is a surround system with diameter of 3.5 m and height of 3 m, and the name implies mobility and portability, while suggesting the immersive nature of the system. The 15-monitor setup (Figure 3) is attached to a custom-made aluminum truss structure. The installation features a borderless design with a 0.9 mm bezel and pull-out mount on custom video wall mounts for quick installation and maintenance. The side monitors (three screens on each edge) can easily be adopted to either 120- or 90-degree placements. There is also a high brightness and resolution projector, located at the top middle of the truss structure, which displays special effects and multimedia content onto a specific floor surface made by a special reflective material of high strength and reflectivity. The system is controlled/driven by a computer with two Intel Xeon Gold 6230 2.1GHz-3.9GHz CPUs, 256GB RAM, storage of 1TB SSD and 8TB HDD, and four PNY NVIDIA Quadro RTX A5000 graphics cards, each with 24 GB memory and able to drive up to four monitors. An NVIDIA Quadro Sync II card synchronizes the four GPUs, enabling the 15 synchronized displays to be controlled by this single computer. The visualization uses the NVIDIA Mosaic technology (connections are made with DisplayPort cables), which allows the configuration of a multi-display setup. The system is completed with a ZED2i tracking camera for motion and gesture recognition that allows for positional tracking, spatial mapping, object detection, and body tracking. A 5.1 surround system delivers the sound of the MobiCave.

Figure 3. Building the VR CAVE "MobiCave".

We tested the VR environment thoroughly to ensure that it was working as expected and made any necessary changes and refinements to improve the overall experience. Adjustments were made regarding the display settings and graphics card software to use multiple monitors. Moreover, the depth camera was tested in various positions and conditions to optimize the spatial detection of persons and objects. During this test-and-refine stage, we experimented with ready-made games as well as custom-made demos.

By following the above steps, we managed to build a VR interactive multiple-monitor setup for gaming that provides a smooth and immersive gaming experience.

4. User Study

A user study was designed to examine the interaction and the overall experience within the MobiCave, through a short gaming task. By using a demo escape room game, we wanted to investigate the following: (1) immersion and sense of presence within the virtual gaming environment, (2) usability and comfort with the players' physical movement and navigation, (3) positive and negative effects of this VR experience, and (4) further possible uses of this setup.

4.1. Participants

A total of 33 users participated in this study. The participant pool consisted of 4 females and 29 males, of which 30 were undergraduate students, 1 postgraduate, and 2 academic staff. Participants were informed of the potential benefits of this research (how the study may contribute to scientific knowledge or have practical applications) and any potential risks or discomfort that they may experience (e.g., simulation sickness). Moreover, their privacy is protected, including the use of pseudonyms and the confidentiality of their responses, and they were informed that their participation is voluntary.

There were no inclusion or exclusion criteria or other requirements for participating in this study, such as previous experience with VR. In this respect, 2 of the participants reported frequent (more than 3 times per week) experience with VR equipment and 12 occasional (Figure 4); 12 participants reported having never used VR equipment before, while 7 of them have novice experience.

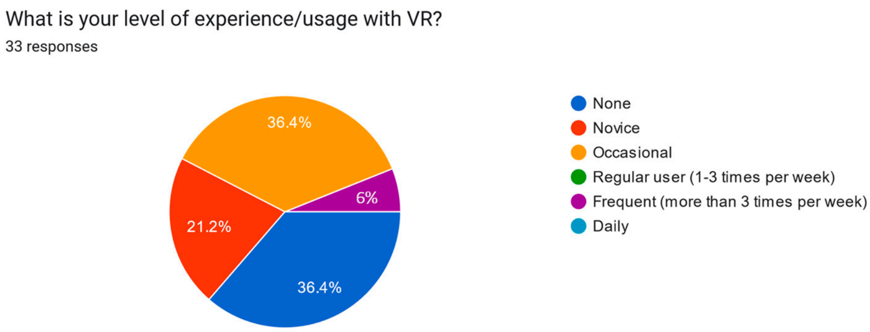

Figure 4. Participants' level of experience/usage with VR.

4.2. Procedure

The experiments conducted were a preliminary demo project, which aimed to test the basic functionality and usability of the virtual environment. As a result, the decision was made to exclude the projector from the demo project, but it is planned to be tested in future studies. The purpose of the demo project was to lay the groundwork for more extensive studies, which will include the testing of the overhead projector and other additional features of the virtual environment.

MobiCave is installed at the HCI-VR laboratory, University of the Peloponnese (https://hci-vr.dit.uop.gr/, accessed on 13 April 2023). Participants were asked to experience a short game demo in the VR CAVE, individually, while others could watch. The game demo is a VR escape room which aims to immerse players in a virtual environment where they must solve puzzles and complete challenges to escape. The game environment is a castle state, where the player sees stone paths and houses while she/he navigates around. For this experiment, the projector at the top of the system described in Section 3 was not used.

As seen in Figure 5, players used their body to navigate into the virtual world and no wearables or other equipment such as HMDs or joysticks were used. With the motion tracking system, they had to use their hands for viewing and rotating in the scene (up, down, left, and right), while their right leg was used for forward and backward movement. The interaction in the game requires the player to be in a standing position 2–2.5 m away from the screens. Before running the experiment, it was tested by two of the laboratory's members to identify any issues or problems and make necessary adjustments (e.g., motion capture camera placement). All the participants were informed of how to control the system and then they experienced the game. After the gameplay, they filled out a survey to evaluate immersion, presence, task difficulty, usability, comfort, and potential usage. The entire gaming session took an average of 5 min to complete, followed by a 5 min time for the survey.

Figure 5. Players experiencing MobiCave.

Finally, the process for the development of the VR interactive CAVE was iterative. Each phase was repeated, implementing changes that we identified in the previous round. For example, some game mechanic elements in the design phase lead us to re-determine the gaming environment of the first phase.

4.3. Metrics

The questionnaires gathered feedback of university students' experience with the game in MobiCave. The survey concerned factors adopted from prior studies: Immersion (IMM), Presence (PRE), Flow (FLO), Perceived Usability (PER_USA), Challenge (CHA), Positive Effects (POS), Negative Effects (NEG), possible usage of this setup for Enjoyment purposes (ENJ), for Learning purposes (LEA), and for the Motivation regarding the bystanders (MOT). In Table 2, we summarize the operational definitions and descriptions of these factors, the items, and their respective bibliographical sources.

Table 2. The research factors in this study and their corresponding items.

Construct	Item Description in the Survey	Factor	Source
Immersion–Presence–Flow	I was interested in the task	IMM1	[64,65]
	I found it impressive	IMM2	[64,65]
	Do you think this setup is immersive?	IMM3	[66]
	I felt like being there, into the scene	PRE	[67,68]
	I forgot everything around me	FLO1	[66,67,69]
	I felt completely absorbed	FLO2	[66,67,69]
Perceived Usability	I thought the VR navigation technique was easy to use	PER_USA1	[64,65]
	I found the VR navigation technique unnecessarily complex	PER_USA2	[64,65]
	I think that I would like to use this VR navigation technique frequently	PER_USA3	[64]
	I think that I would need the support of a technical person to be able to use this VR navigation technique	PER_USA4	[64]
	I felt very confident using the VR navigation technique	PER_USA5	[64]
	-	PER_USA6	[64]
Comfort—Positive and Negative aspects	I felt challenged (Positive Challenge)	CHA1	[64,66,68]
	I had to put a lot of effort into it (Negative Challenge)	CHA2	[64,65]
	I felt good (Positive Effect)	POS1	[64,65,69]
	I felt skillful (Positive Effect, Competence)	POS2	[64,65,68]
	I felt bored (Negative Effect)	NEG1	[64,65,69]
	I found it tiresome (Negative Effect)	NEG2	[64,65,69]
	Did you experience any simulation sickness?	SIC	[70]
Possible Usage	Do you think this setup can be good for playing games? (Enjoyment)	ENJ	[71,72]
	Do you think this setup can have learning impact e.g., for students visiting the university? (Learning)	LEA	[73,74]
	Do you think this setup can be good for the bystanders to be part of the experience? (Motivation-Engagement)	MOT	[71,75]

In all measures, a 5-point Likert scale was applied (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree).

4.4. Hypotheses—Analysis

As aforementioned, 33 university students were involved in playing the demo escape room game in the MobiCave. We would expect users to find this VR monitor setup highly immersive (**H1**) as they explore the virtual space. Given that they used their body to play the game and to move around in the scene, we would expect to find this navigation useful and easy to use (**H2**). We would also expect them to have more positive effects than negative ones, regarding the comfort and possible skills and challenges they faced in the game (**H3**). Finally, regarding possible uses of this VR CAVE setup, we would expect them to find it suitable for both learning and fun purposes (**H4**).

To test each hypothesis (H1, H2, H3, H4), we analyzed descriptive statistics (frequencies) of the data. The samples had homogenous variances and normal distribution of data.

We also ran Spearman's correlation tests for the Likert analyses to determine whether there was a correlation between the different variables being measured for each hypothesis. Finally, except for the data provided in Table 2, this study gathered information by observing the users—players—and by responses on the following open-ended question at the end of the survey, "*What else do you believe would enhance your virtual experience in the tunnel? Please write your thoughts*". These data provide a means to explain and validate the results.

4.5. Results

In this section, we present the results obtained from the answers, based on the 5-point Likert scale of items in Table 2.

(H1). Immersion, Presence, and Flow.

Users rated the immersion and presence of the gaming experience as an average of 4,36 for IMM1, 4,39 for IMM2, 4,31 for IMM3, and 3,7 for PRE (Table 3). Regarding flow (Figure 6), n = 16 users (12 agree + 4 strongly agree) reported that they forgot everything around them (FLO1), and n= 19 (11 agree + 8 strongly agree) stated that they felt completely absorbed (FLO2).

Table 3. Summary of measurements.

Construct	Item	Mean	SD
Immersion–Presence–Flow	IMM1	4.36	0.783
	IMM2	4.39	0.747
	IMM3	4.21	0.600
	PRE	3.70	0.984
	FLO1	3.27	1.126
	FLO2	3.61	1.116
Perceived Usability	PER_USA1	3.48	1.093
	PER_USA2	1.97	1.075
	PER_USA3	3.82	0.808
	PER_USA4	2.15	1.253
	PER_USA5	3.70	1.045
	PER_USA6	4.03	0.984
Comfort—Positive and Negative aspects	CHA1	3.67	1.164
	CHA2	3.00	1.061
	POS1	4.61	0.556
	POS2	3.79	1.193
	NEG1	1.21	0.485
	NEG2	2.00	1.173
	SIC	1.45	1.003
Possible Usage	ENJ	4.61	0.556
	LEA	4.52	0.834
	MOT	4.15	0.939

Additionally, our observations show that the VR setup gives the player the ability to feel that she/he is being present in the virtual environment, rather than the real space.

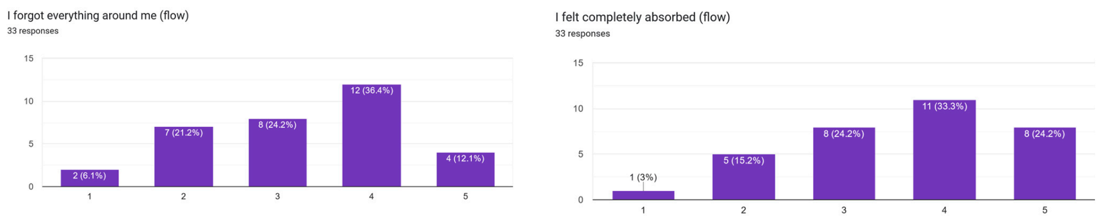

Figure 6. Players' responses on flow factors, on a 5-point Likert scale, with 1 as strongly disagree and 5 as strongly agree (left FLO1, right FLO2).

Moreover, Spearman's rank-order correlation was run to determine the relationship between constructs of H1 (Table 4). There was a strong, positive correlation which was statistically significant between IMM1 and IMM3 ($r_s(31) = 0.563$, $p < 0.001$), between IMM1 and PRE ($r_s(31) = 0.533$, $p = 0.001$), between IMM2 and IMM3 ($r_s(31) = 0.472$, $p = 0.006$), between IMM2 and FLO2 ($r_s(31) = 0.518$, $p = 0.002$), between IMM1 and PRE ($r_s(31) = 0.533$, $p = 0.001$), between IMM3 and FLO1 ($r_s(31) = 0.363$, $p = 0.038$), between IMM3 and FLO2 ($r_s(31) = 0.418$, $p = 0.015$), between IMM3 and FLO1 ($r_s(31) = 0.363$, $p = 0.003$), and between FLO1 and FLO2 ($r_s(31) = 0.751$, $p < 0.001$).

Table 4. Correlations table on Immersion–Presence–Flow.

		IMM1	IMM2	IMM3	PRE	FLO1	FLO2
IMM1	Correlation Coefficient	1,000	0.337	**0.563** **	**0.533** **	0.215	0.131
	Sig. (2-tailed)	0	0.055	**<0.001**	**0.001**	0.230	0.467
	N	33	33	33	33	33	33
IMM2	Correlation Coefficient	0.337	1,000	**0.472** **	0.260	0.220	**0.518** **
	Sig. (2-tailed)	0.055	0	**0.006**	0.144	0.219	**0.002**
	N	33	33	33	33	33	33
IMM3	Correlation Coefficient	**0.563** **	**0.472** **	1,000	0.338	**0.363** *	**0.418** *
	Sig. (2-tailed)	**<0.001**	**0.006**	.	0.055	**0.038**	**0.015**
	N	33	33	33	33	33	33
PRE	Correlation Coefficient	**0.533** **	0.260	0.338	1,000	0.278	0.265
	Sig. (2-tailed)	**0.001**	0.144	0.055	.	0.117	0.136
	N	33	33	33	33	33	33
FLO1	Correlation Coefficient	0.215	0.220	**0.363** *	0.278	1,000	**0.751** **
	Sig. (2-tailed)	0.230	0.219	**0.038**	0.117	.	**<0.001**
	N	33	33	33	33	33	33
FLO2	Correlation Coefficient	0.131	**0.518** **	**0.418** *	0.265	**0.751** **	1,000
	Sig. (2-tailed)	0.467	**0.002**	**0.015**	0.136	**<0.001**	.
	N	33	33	33	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed). Bold values are significant.

Consequently, H1 was found true to a significant extent. The players reported very positive results in disconnection from the real world and real time, along with involvement in the game environment.

(H2). Perceived Usability.

Most participants found the VR navigation technique easy to use (PER_USA1, $n = 17$) and not unnecessarily complex (PER_USA2, $n = 24$). Only a few of them had some initial problems when they tried to move in the virtual world since they teleported themselves against walls or used their body to interact (walk and move around) like in the physical space. Most participants were able to interact with the VR environment without further guidelines (PER_USA4, $n = 24$) and suggested that they would like to use this VR navigation technique frequently (PER_USA3, $n = 23$). They also felt very confident using it (PER_USA5, $n = 21$). Finally, most users believe that most people can learn to use this navigation technique very quickly (PER_USA6, $n = 25$) as it is realistic and natural.

Moreover, Spearman's correlation was run to determine the relationship between constructs of H2 (Table 5). There was a strong, positive correlation which was statistically significant between PER1 and PER3 ($r_s(31) = 0.381$, $p = 0.029$), between PER1 and PER6 ($r_s(31) = 0.487$, $p = 0.004$), and between PER5 and PER6 ($r_s(31) = 0.462$, $p = 0.007$).

Table 5. Correlations table on Perceived Usability.

		PER1	PER2	PER3	PER4	PER5	PER6
PER1	Correlation Coefficient	1,000	0.210	**0.381 ***	0.089	0.219	**0.487 ****
	Sig. (2-tailed)	.	0.240	**0.029**	0.621	0.222	**0.004**
	N	33	33	33	33	33	33
PER2	Correlation Coefficient	0.210	1,000	0.130	0.204	−0.034	−0.108
	Sig. (2-tailed)	0.240	.	0.469	0.254	0.852	0.551
	N	33	33	33	33	33	33
PER3	Correlation Coefficient	**0.381 ***	0.130	1,000	0.172	0.208	0.207
	Sig. (2-tailed)	**0.029**	0.469	.	0.339	0.246	0.247
	N	33	33	33	33	33	33
PER4	Correlation Coefficient	0.089	0.204	0.172	1,000	−0.209	−0.305
	Sig. (2-tailed)	0.621	0.254	0.339	.	0.243	0.085
	N	33	33	33	33	33	33
PER5	Correlation Coefficient	0.219	−0.034	0.208	−0.209	1,000	**0.462 ****
	Sig. (2-tailed)	0.222	0.852	0.246	0.243	.	**0.007**
	N	33	33	33	33	33	33
PER6	Correlation Coefficient	**0.487 ****	−0.108	0.207	−0.305	**0.462 ****	1,000
	Sig. (2-tailed)	**0.004**	0.551	0.247	0.085	**0.07**	.
	N	33	33	33	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed). Bold values are significant.

Therefore, H2 was found to be true. Given that users used their body to play the game and to move around in the scene, they found this navigation useful and easy to use.

(H3). Comfort—Positive and Negative aspects.

To evaluate the construct of comfort, we measured negative aspects (e.g., boredom and tiredness), positive aspects (e.g., feeling and competence), and challenges (e.g., effort and task). As shown in Figure 7, most users felt challenged (agree and strongly agree responses reached 60.3%) and they had to put average to little effort to complete the task (mean = 3.00). In total, almost all users ($n = 32$) rated that they felt good (POS1) by interacting in this environment, while $n = 24$ felt skillful (POS2). The resulting answers indicate significantly below average negative effects of feeling bored (NEG1, mean = 1.21) and becoming tired (NEG2, mean = 2.00).

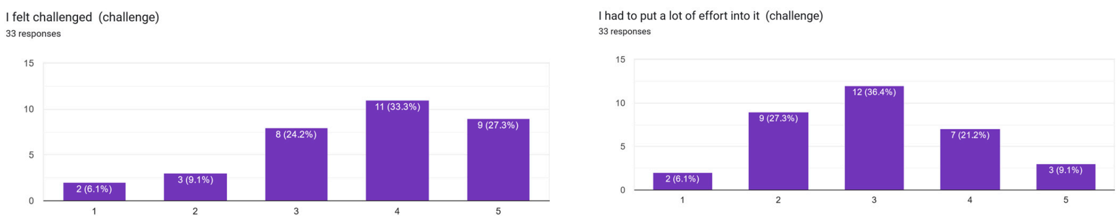

Figure 7. Players' responses on challenge factors, on a 5-point Likert scale, with 1 as strongly disagree and 5 as strongly agree (left CHA1, right CHA2).

Additionally, Spearman's rank-order correlation was run to determine the relationship between constructs of H3 (Table 6). There was a strong, positive correlation which was statistically significant between CHA2 and NEG1 ($r_s(31) = 0.439$, $p = 0.011$), between POS1 and POS2 ($r_s(31) = 0.558$, $p < 0.001$), and between POS1 and NEG2 ($r_s(31) = -0.507$, $p = 0.003$).

Table 6. Correlations table on Comfort—Positive and Negative aspects.

		CHA1	CHA2	POS1	POS2	NEG1	NEG2	SIC
CHA1	Correlation Coefficient	1,000	0.324	0.218	0.355 *	0.065	−0.111	0.080
	Sig. (2-tailed)	.	0.066	0.223	0.043	0.718	0.539	0.657
	N	33	33	33	33	33	33	33
CHA2	Correlation Coefficient	0.324	1,000	−0.054	−0.049	**0.439 ***	0.110	0.288
	Sig. (2-tailed)	0.066	.	0.766	0.786	**0.011**	0.541	0.104
	N	33	33	33	33	33	33	33
POS1	Correlation Coefficient	0.218	−0.054	1,000	**0.558 ****	−0.160	**−0.507 ****	0.022
	Sig. (2-tailed)	0.223	0.766	.	**<0.001**	0.373	**0.003**	0.902
	N	33	33	33	33	33	33	33
POS2	Correlation Coefficient	**0.355 ***	−0.049	**0.558 ****	1,000	−0.326	−0.095	0.008
	Sig. (2-tailed)	**0.043**	0.786	**<0.001**	.	0.064	0.599	0.966
	N	33	33	33	33	33	33	33
NEG1	Correlation Coefficient	0.065	**0.439 ***	−0.160	−0.326	1,000	0.331	−0.024
	Sig. (2-tailed)	0.718	**0.011**	0.373	0.064	.	0.060	0.894
	N	33	33	33	33	33	33	33
NEG2	Correlation Coefficient	−0.111	0.110	**−0.507 ****	−0.095	0.331	1,000	0.019
	Sig. (2-tailed)	0.539	0.541	**0.003**	0.599	0.060	.	0.917
	N	33	33	33	33	33	33	33
SIC	Correlation Coefficient	0.080	0.288	0.022	0.008	−0.024	0.019	1,000
	Sig. (2-tailed)	0.657	0.104	0.902	0.966	0.894	0.917	.
	N	33	33	33	33	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed). Bold values are significant.

Thus, H3 was found to be true.

(H4). Possible Usage.

To research possible usages of MobiCave, participants were asked about playing games for enjoyment purposes (ENJ), about learning purposes (e.g., for students visiting the university, LEA), and whether it can be helpful for the bystanders as being part of the experience. The players indicated that the overall experience was motivating and engaging (AVG = 4.61, SD = 0.556), and overall, they found it enjoyable. Most of them reported that they would like to learn with this setup (AVG = 4.52, SD = 0.834), and outlined that concepts are easier to understand using immersive environments like this. Being part of this experience as bystanders also seems to be a very useful aspect for them (AVG = 4.15, SD = 0.939). Suggestions for improvements concerned making the games look even more realistic, further improving the visualizations.

Finally, Spearman's rank-order correlation was run to determine the relationship between constructs of H4 (Table 7). There was a strong, positive correlation which was statistically significant between LEA and MOT ($r_s(31) = -0.369$, $p = 0.035$).

Table 7. Correlations table on Possible Usages of MobiCave.

		ENJ	LEA	MOT
ENJ	Correlation Coefficient	1,000	0.257	0.305
	Sig. (2-tailed)	.	0.148	0.084
	N	33	33	33
LEA	Correlation Coefficient	0.257	1,000	**0.369 ***
	Sig. (2-tailed)	0.148	.	**0.035**
	N	33	33	33
MOT	Correlation Coefficient	0.305	**0.369 ***	1,000
	Sig. (2-tailed)	0.084	**0.035**	.
	N	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed). Bold values are significant.

Therefore, H4 was found to be true.

5. Discussion—Challenges and Opportunities

The user study we conducted showed great potential for MobiCave, because all hypotheses were found to be true. Users found the VR setup highly immersive as they explored the virtual space. They found the navigation useful and easy to use, using their body to play the game and move around in the scene. They also had only positive effects regarding the comfort, possible skills, and challenges they faced in the game. Finally, they reported that this VR CAVE environment is suitable for both learning and fun purposes and is motivating for the bystanders. While we did not test bystanders directly, we did gather information about the perceptions of our participants regarding bystanders. Further research could be conducted to explore the effects of bystanders on the overall immersive experience.

It seems that the potential applications of MobiCave are numerous, with possibilities ranging from entertainment to education and training. In the entertainment industry, interactive VR CAVEs could provide a more immersive and engaging gaming experience than traditional games, attracting a new audience of gamers. In training, they could simulate real-world environments, allowing users to practice skills and techniques in a safe and controlled environment. In learning, they could provide a fun and interactive way to educate children and young adults on important topics. This setup can provide an immersive and interactive experience that can be both engaging and memorable. Moreover, the bystanders can experience and understand the impact of players' behavior during the gameplay around them. The focus in this study was on studying individual user behavior and perception in the immersive environment, rather than interactions between multiple users. Future work will involve collaborative and social interactions in MobiCave by two players.

One of the main technical challenges of developing such a VR CAVE is ensuring that the virtual environment is responsive to the movements of the players. This requires accurate motion tracking and the ability to update the visual and auditory feedback in real-time. Haptic devices, such as gloves and wearables, may enhance the sense of immersion by providing tactile feedback to the player. However, they should be used carefully, as the choice of the body being the controller (without other accessories) has several advantages in certain scenarios (e.g., school visit to an exhibition where the users alternate continuously). Another challenge is designing special game mechanics to make full use of the immersive environment. In traditional gaming, the player typically interacts with a flat screen, using a controller or keyboard to input commands. In an interactive VR environment, the player's entire body is involved in the gameplay, which opens a wide range of new possibilities for game mechanics. For example, players can physically interact with objects in the environment, for example picking up and throwing items, or they can collaborate with other players to solve puzzles. In [4], there is such a mechanic where in multiplayer mode (two players in front of the VR system) players can share their vitality by a corporate gesture. These added capabilities also pose new challenges. In our experiment, even though navigation is rather simple, some users reported that there should be some navigation gesture examples at first (e.g., the right way to use hands for turning).

The development of an interactive VR CAVE raises interesting questions about the role of bystanders in the gaming experience. The proposed setup can provide a social experience that is not possible with traditional gaming or even with several established VR setups where the player is isolated from the bystanders. Players and bystanders can collaborate, compete, and communicate with each other in real time, creating a sense of shared experience and community. The MobiCave allows bystanders to watch the players' actions directly; therefore, future games in this setup should create opportunities for participation, such as allowing them to control certain elements of the environment or provide feedback to the players. This could create a more engaging and interactive experience for all involved. Ultimately, the role of bystanders in the MobiCave will depend on the goals of the game design and the preferences of the players. It is important to consider the needs and desires of all stakeholders in the gaming experience, including those who may not be directly participating. By taking a holistic approach to game design, we can create immersive and engaging experiences that are inclusive for all.

There are also some more implications of the technology used for building similar VR setups. The diameter and height of the truss structure should be carefully considered to ensure that it provides enough space for players to move around comfortably while also being large enough to create an immersive experience. The monitor setup with the borderless design and pull-out mount should make it easy to install and maintain the displays. Furthermore, the computer hardware is crucial for the performance of the VR system. The graphics cards should enable high-quality graphics rendering and smooth performance while the synchronization of the GPUs should ensure that the displays are synchronized and provide a seamless experience.

While the development of interactive public VR environments for immersive shared gaming experiences has great potential, there are also some limitations that need to be addressed. One limitation is the cost of the hardware required to create an interactive VR CAVE. Special monitors, motion tracking sensors, and specific truss systems can be expensive, which could limit the accessibility of this technology. Another limitation is the potential discomfort among players. Because an interactive VR CAVE requires players to physically move and interact with their environment, some users may experience discomfort or motion sickness. In our study, one user reported that she felt sick after a while. This could be addressed by limiting the length of gameplay sessions. The social implications of immersive shared gaming experiences should also be considered. While this technology has the potential to bring people together in new and exciting ways, it also has the potential to reinforce existing power dynamics and social hierarchies. Developers should consider the potential impact of their games on social dynamics and work to create inclusive and equitable gaming experiences. Overall, while there are limitations to the development of interactive VR CAVEs for immersive shared gaming experiences, these challenges can be addressed through continued innovation and collaboration among developers, researchers, and stakeholders. With careful consideration of these limitations, developers can create immersive and engaging gaming experiences that are accessible, inclusive, and enjoyable for all. MobiCave offers a valuable contribution to the field of immersive VR. Specifically, our system is designed to be affordable and easy to use (mobility and portability), making it accessible to a wider range of users. Additionally, our system addresses some of the limitations of previous solutions, such as the need for a dedicated physical space or the high cost of specialized equipment.

6. Conclusions

The use of VR technology in public spaces has opened new possibilities for immersive shared gaming experiences. Multi-user setups and public interactive VR CAVEs have the potential to create new forms of social interaction and collaboration in gaming. This work presents the design and development of MobiCave, an interactive VR environment for shared gaming experiences. A user study was conducted that aimed to gather feedback from university students regarding their experience with a demo escape room game in the MobiCave. Results have shown promising findings in both fun and learning purposes, providing an immersive experience for both players and bystanders.

As a next step, we plan to use MobiCave with the public and especially young people. This will provide us withfurther feedback to improve the VR environment and future games. We also develop games and interactive experiences to enhance the role of bystanders in the MobiCave. We aim to make immersive, captivating, and inclusive games by approaching game design holistically. Additionally, we plan to introduce odors in the VR tunnel, e.g., the smell of fire, and test it out in gaming and simulation scenarios.

In closing, immersive gaming technologies in public spaces can provide a range of benefits. Although there are challenges to be addressed in the proposed setup, the possibilities for entertainment, education, and social interaction are vast. As this technology evolves, it will be exciting to see how it transforms the way we experience digital content.

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