

POLITECNICO DI TORINO

Master's thesis in Engineering and Management



A Comparative Study of Immersive Virtual Reality Systems: Technological, Experiential, and Economic Perspectives

Supervisors:

Prof. Francesca Nonis

Candidate:

Francesco Nappo

Co-Supervisors:

Prof. Federica Marcolin

Prof. Alessia Celeghin

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Abstract

The thesis investigates immersive virtual reality technologies by analyzing the principal differences between Desktop VR, Head-Mounted Displays (HMDs) and CAVE systems from technological, experiential and economic perspectives. The different parameters analyzed between these technologies are immersion, interaction, accessibility, scalability, collaboration and infrastructural complexity; advantages and limitations related to the context and the objective of the different studies are highlighted. The systems mainly reviewed are the CAVE virtual reality environments and their role in emotional and behavioral research. Different experiments within CAVE are studied to understand how virtual scenarios influence emotional responses, stress levels, cognitive workload and user behavior. Alongside the analysis of representative experiments reported, the thesis presents and discusses a case study developed within the CAVE laboratory of the CIM 4.0 Competence Center at the Polytechnic of Turin. Making full use of existing literature, the study examines the principal validated questionnaire primarily employed in immersive virtual reality research affiliated with presence, emotional assessment, workload, situational awareness and usability to identify the indicators from validated psychometric tools most relevant to the proposed experimental analysis. In addition the thesis regards the economic analysis of virtual reality technologies. The cost structure of Desktop VR, HMDs, and CAVE systems are distinguished to highlight the differences between hardware requirements, infrastructure, maintenance, portability and scalability. It is demonstrated that economic accessibility significantly influenced the historical evolution and market diffusion of immersive technologies. Consequently, linked factors of market adoption are analyzed that drove the estimated trends in the market popularity of these systems, placing a significant emphasis on HMD technology, which has experienced substantial shifts in market perception. The thesis explores the future perspectives of CAVE systems, highlighting their continuing relevance within collaborative, industrial and research-oriented applications. Potential future developments involving artificial intelligence, mixed reality, digital twins and advanced multisensory systems are also discussed, suggesting that CAVE environments may continue evolving through a synergistic approach between existing technologies and emerging innovations.

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Introduction

Virtual reality (VR) has evolved from its origins in highly specialized technological and military applications into a pivotal tool for research across the medical, educational, and entertainment sectors. This study analyzes the operational mechanisms underlying virtual reality technologies, with a specific and in-depth focus on the CAVE (Cave Automatic Virtual Environment) system. Particular attention is devoted to the spatial configurations that characterize these experimental environments as well as the formulation of assessment metrics typical of evaluation surveys. Subsequently, the study compares findings from existing literature with an empirical experiment on human emotional behavior that will be conducted at CIM4.0, the innovation and advanced training competence center founded by the Polytechnic of Turin and the University of Turin, and identify the indicators from validated psychometric tools most relevant to the proposed experimental analysis. Furthermore, this research incorporates a cost analysis of these technologies and examines their historical trends, seeking to elucidate the underlying causes for fluctuations in their popularity over time. Virtual reality is recognized as a multidisciplinary field that supports human activities in myriad ways. Finally, the study concludes by outlining the prospective roles this technology may assume, driven by future developments that favor synergistic, rather than mutually exclusive, technological approaches.

1. Major Virtual Reality Technologies

1.1 Introduction to Virtual Reality

Virtual Reality (VR) refers to a set of advanced technologies designed to enable users to experience and interact with computer-generated environments that simulate either real or imagined scenarios. Unlike traditional human-computer interaction systems, which are generally mediated through two-dimensional interfaces such as monitors, keyboards and pointing devices, VR aims to create immersive experiences in which users perceive themselves as physically present within a digital environment. The key point in the evolution of human interaction with digital transformation is the shift from passive observation to active immersion. To understand how well a virtual reality simulates the real world, three parameters are fundamental: immersion, presence and agency. Immersion is linked to the technological features of the system that depend on visual rendering quality, field of view, spatial audio and haptic feedback. These elements determine the extent to which virtual stimuli are capable of replacing sensory input originating from the physical world [1], [2]. Presence represents a subjective psychological response that describes the sensation of “being there” within the virtual environment despite the user’s physical location remaining unchanged. This perception depends not only on technological factors but also on the coherence, consistency, and realism of the virtual scenario [3]. Agency refers to the user’s perceived ability to act within the virtual environment and observe the consequences of those actions in real time. It is strongly associated with the sense of control playing a central role in shaping both cognitive and emotional responses [4], [5]. A high level of agency allows users to feel actively involved in the virtual experience rather than merely observing it passively, thereby increasing engagement and perceived realism. Decision-making processes and behavioral reactions are directly affected from agency, particularly in stress and risk scenarios [6], [7]. The evolution in the last decades has been very rapid and involved industrial and consumer contexts, widening the range of VR application including simulations, medical rehabilitation, architectural visualization, education, tourism, marketing, and entertainment [6]–[9]. Then the ability of reproducing controlled experimental condition creates interest into the VR research field,

especially in scientific studies because maintaining consistency across participants while changing specific variable is essential for the experiment interest [10]. The principal categories include desktop-based virtual reality systems, head-mounted displays (HMDs), and projection-based systems such as CAVE (Cave Automatic Virtual Environment) [11]–[13]. Each of these technologies presents specific advantages and limitations, making them suitable depending on the objectives, users and application domains considered.

1.2 Main Categories of Virtual Reality Systems

The differences between the desktop VR, CAVE systems and HMD are shown in the user experience analysis. Some systems primarily emphasize accessibility, affordability, and ease of use, whereas others are designed to maximize immersion and perceptual realism, often requiring greater infrastructural complexity and higher resource investment. Since the primary objective of a research is founding the appropriate technology for a specific context or research objective, it is crucial to understand the characteristics and the limitations of the three technologies

1.2.1 Desktop Virtual Reality

Desktop Virtual Reality represents one of the most traditional and accessible forms of interaction with virtual environments. As shown in Figure 1, the virtual world is displayed through a standard computer monitor, while users interact with the environment using conventional input devices such as keyboards, mice, or game controllers. Unlike fully immersive systems, desktop VR does not seek to replace the user's sensory perception of the physical world, but rather to provide access to a simulated environment through a mediated visual interface. Studying the technological aspects of Desktop VR, it is simple to implement hardware and software infrastructures and have high scalability. The creation of three-dimensional environments is permitted by conventional graphics processing units. This contributes to the widespread adoption of desktop VR in different fields [14]. The strengths of Desktop VR are the ease of use and the low barrier to entry, also allowing straightforward integration with additional software tools deployed across multiple devices with limited technical complexity. These characteristics make desktop VR particularly suitable for collaborative or distributed scenarios in which multiple users need to access the same virtual environment independently [15], [16]. On the other hand, the limitations of desktop VR

become more apparent when considering dimensions such as immersion, presence, and agency. The user's field of view is restricted by the physical dimensions of the monitor and the surrounding real-world environment remains fully visible, in addition the interaction is mediated through indirect input devices, limiting the naturalness of user actions and reducing the perceived level of agency. Those are the reasons why the sense of presence within the virtual environment is considerably reduced. As summarized in Table 1, Desktop VR generally provides lower levels of immersion, presence, and agency when compared with HMD and CAVE systems.



Figure 1: Example of Desktop VR setup

1.2.2 Head-Mounted display (HMDs)

Head-Mounted Displays (HMDs) represent a significant advancement in virtual reality technology, offering users highly immersive experiences through wearable devices capable of fully or partially occluding the surrounding physical environment; Figure 2 clearly illustrates how the user is fully immersed in the virtual environment through the use of a head-mounted display (HMD), which provides a comprehensive visual experience and effectively isolates the

user from visual stimuli originating in the physical world. These systems generally consist of headsets equipped with high-resolution displays, motion-tracking sensors and, in many cases, integrated audio technologies. By continuously tracking the user's head movements in real time, HMDs dynamically adapt the visual perspective of the virtual environment, thereby creating a strong illusion of spatial presence [17] and enhancing depth perception and spatial awareness [18]. These characteristics contribute to the high levels of immersion and presence associated with HMD technologies, as illustrated in Table 1.

Contemporary HMDs frequently incorporate handheld controllers or advanced hand-tracking technologies, enabling users to interact with virtual objects in a more natural and intuitive manner [19]. Even with these advantages, HMD systems also present several limitations and challenges. Cybersickness is among the most commonly reported issues, representing a form of motion sickness caused by discrepancies between visual stimuli and the user's physical movements. Symptoms associated with cybersickness may negatively affect user comfort and limit the duration of immersive sessions [20], [21]. The prolonged use of headsets may generate physical discomfort due to factors such as device weight, heat generation, visual fatigue, and ergonomic limitations [22]. The disadvantages of HMDs may also influence the experimental setting. Because users are visually isolated from the surrounding environment, opportunities for direct social interaction and collaborative engagement can be reduced. This aspect becomes particularly relevant in research contexts where group dynamics, shared experiences or interpersonal communication constitute important experimental variables [23]. Confronting advantages and disadvantages, HMDs remain among the most effective technologies for generating high levels of immersion and emotional engagement, particularly in contexts where a strong sense of presence is essential [24].



Figure 2: Example of HMD VR setup

1.2.3 CAVE Systems

CAVE (Cave Automatic Virtual Environment) systems represent a projection-based approach to immersive virtual reality, relying on large-scale visualization technologies rather than wearable devices. A typical CAVE consists of a room-sized environment in which images are projected onto multiple surfaces, including walls and floors, generating a surrounding visual field that envelops the user. These projections are generally stereoscopic and synchronized across all surfaces to create a coherent and immersive three-dimensional experience. Figure 3 illustrates how visual projections can be extended to the floor of the CAVE environment, enabling a more realistic perception of space and improving users' ability to estimate distances within the virtual scenario. This capability is made possible by the advanced integration of stereoscopic projection systems and specialized visualization glasses, which together create a highly immersive and spatially coherent virtual environment. CAVE systems allow participants to remain partially aware of the real space around them and to interact directly with other individuals located within the same environment [21], [25]. Thanks to this characteristic, projection-based immersive systems are particularly suitable for collaborative applications,

including design reviews, training simulations, and multi-user experimental studies. These environments are commonly equipped with advanced tracking technologies capable of monitoring the position and orientation of users, with particular attention devoted to head and body movements. The collected tracking data are used to update projected images in real time, ensuring that the visual perspective remains coherent with the user's viewpoint. Consequently, users experience elevated levels of presence and agency, as their movements are immediately reflected within the virtual environment. The integration of large-scale projection surfaces also provides a wide field of view without requiring head-mounted equipment. This contributes to a more natural interaction experience, allowing users to move freely while maintaining peripheral awareness of both the virtual and physical environments. The absence of wearable devices reduces physical discomfort and supports longer interaction sessions; CAVE technology allows the course of progress of long experiments. On the other hand, CAVE systems involve considerable infrastructural complexity. Their implementation requires substantial physical space, specialized hardware and complex calibration procedures necessary to maintain accurate alignment and synchronization across projection surfaces. These requirements contribute to high installation and maintenance costs, limiting the accessibility of such systems primarily to research institutions, industrial facilities, and specialized laboratories. As reported in Table 1, this combination of immersion and environmental awareness represents one of the distinctive characteristics of CAVE-based virtual reality systems.

Within the context of experimental research, CAVE systems provide a distinctive combination of immersion, environmental control, and ecological validity. Their capacity to reproduce realistic virtual scenarios while preserving natural interaction and social presence makes them especially valuable for investigating human emotions, behavioral responses, and decision-making processes. Table 1 further highlights how CAVE systems combine collaborative capabilities, natural interaction, and high levels of presence more effectively than many alternative VR configurations.



Figure 3: Example of CAVE system setup

1.3 Comparison Between Desktop VR, HMDs and CAVE Systems

The principal differences between Desktop VR, HMDs, and CAVE systems are summarized in Table 1. Desktop VR offers a relatively limited degree of immersion since the virtual

environment remains confined to a two-dimensional display and users continue to perceive the surrounding physical space without interruption. HMDs provide a substantially higher level of immersion by occupying the user's field of view and replacing real-world sensory input with virtual stimuli. CAVE systems can be positioned between these two paradigms, as they provide extensive visual immersion through large-scale projections while simultaneously allowing users to preserve awareness of their physical surroundings. Analyzing the technologies in the "presence" perspective, HMDs are generally highly effective in generating it because they minimize external distractions through visual isolation. Simultaneously, this isolation may reduce situational and environmental awareness. CAVE systems, although slightly less immersive in terms of sensory exclusion, provide a more balanced experience by combining immersive visualization with spatial awareness and physical grounding. Desktop VR, by contrast, generally produces lower levels of presence due to its reduced sensory involvement [26]. Third dimension examined is agency; within desktop VR systems, it is frequently constrained by indirect interaction methods, such as mouse and keyboard inputs, which reduce the naturalness of user behavior. HMD-based systems increase the perception of agency through motion-tracking technologies and handheld controllers that support more intuitive forms of interaction. CAVE environments extend this concept further by enabling users to move naturally within a physical space, thereby promoting a more embodied and realistic interaction experience. Desktop VR relies on conventional interfaces that are familiar and accessible, although less immersive. HMDs introduce more natural interaction techniques, even if these are often mediated through controllers or tracking devices. CAVE systems provide a distinctive advantage in this regard, as they support physical movement and real-time interaction without requiring full-body wearable equipment, thereby contributing to a more intuitive and seamless user experience [27], [28].

Finally, social and collaborative interaction. Desktop VR allows multiple users to access the same virtual environment, although generally in a distributed manner without shared physical presence. HMD-based systems tend to isolate users from one another, making direct face-to-face interaction more difficult unless supplementary communication technologies are integrated. CAVE systems, conversely, are inherently well suited to collaborative experiences because multiple participants can simultaneously share the same physical and virtual environment, enabling direct communication and collective interaction [29]. Each

technological approach therefore presents distinct strengths and limitations offering different trade-offs between immersion, presence, agency, collaboration, scalability, and implementation cost. The capacity to balance them represents a fundamental factor in the creation of realistic virtual scenarios and in the elicitation of authentic emotional and behavioral responses [30], [31].

Table 1: Comparative overview of Desktop VR, HMDs, and CAVE systems, adapted from [11]–[14]

Feature	Desktop VR	HMD	CAVE
Immersion	Low	Very High	High
Presence	Low	Very High	High
Environmental Awareness	Very-high	Very Low	High
Agency	Low-moderate	High	Very High
Interaction Modality	Mouse, keyboard, controllers	Motion tracking and controllers	Natural movement and spatial interaction
Naturalness of Interaction	Low	High	Very High
Collaborative Interaction	Moderate	Limited	Very High
Social Presence	Low	Moderate	High
Main Strength	Accessibility and scalability	Immersion and portability	Collaboration and embodied interaction
Main Limitation	Low immersion	Isolation and discomfort	High infrastructure requirements

2 CAVE Systems and Emotional Virtual Environments

2.1 Definition and Operating Principles of a CAVE System

After giving an overview of projection-based virtual reality in the previous chapter, this section will present the CAVE (Cave Automatic Virtual Environment) setup utilized in this study, focusing on the technological framework implemented in the laboratory and the technological components which are used to conduct the experiments described within this thesis. The CAVE system used in this study provides a highly advanced immersion platform suitable for conducting research that requires a high level of visualization, real-time interaction, and synchronization of the technological systems involved. The efficiency of the whole immersive experience does not depend solely on the performance of the technological components, but also on the integration and synchronization of these elements. Integration and synchronization are particularly important in experimental settings where immersion realism, latency, spatial consistency, and interaction precision are essential factors which affect the reliability and quality of collected data [32]–[34]. This is the reason why both hardware and software framework in the presented CAVE system provide stable real-time rendering and visualization, as well as accurate user tracking across all surfaces. It is used as the experimental platform which allows for investigating human emotional states, stress conditions, and decision-making processes in immersive environments. The experiment in question involves cognitive tasks, environmental interaction, and emotional events performed within a particular virtual environment enabling the analysis of participants' behavior and reactions to different stimuli in reproducible conditions. Therefore, the knowledge of the technological structure of the particular CAVE environment is crucial for the understanding of the implementation of the experimental environment as well as for the analysis of results obtained.

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2.2 Hardware and Software Architecture of the Case Study CAVE

This CAVE system is designed to provide a large-scale, projection-based environment in which users can interact naturally with virtual content while maintaining awareness of the physical space. The specific system in analysis has been developed and installed within the Competence Center Industry Manufacturing 4.0 in Turin, Italy, and has been specifically designed to support

applications such as behavioral analysis, usability testing, and professional training in immersive environments. The hardware layer is responsible for generating and displaying high-quality stereoscopic images, as well as tracking user movements with high precision. The software layer, on the other hand, manages rendering processes, multi-screen synchronization, interaction logic, and integration with external tools for content creation and simulation.

2.2.1 Hardware Architecture of the CAVE System

CAVE Structure and Projection Surfaces

Figure 4 illustrates an example of the immersive output generated by the CAVE system adopted in this study. The system is built upon a self-supporting structure based on the BARCO “S4” configuration, which consists of four projection surfaces: three vertical walls and one horizontal floor. The vertical screens are designed for rear projection and have dimensions of approximately 3.2 meters in width and 2.0 meters in height, while the floor screen is based on front projection and measures 3.2 meters in width and 2.5 meters in depth.



Figure 4: Structure of the CAVE system used in the experimental study

This configuration allows for a large field of view and enables users to perceive virtual environments at a 1:1 scale, which is fundamental for applications involving spatial understanding and behavioral analysis. The projection surfaces are made of rigid acrylic material with a specialized coating that enhances optical performance, including brightness,

contrast, and color uniformity. The use of high-contrast coatings reduces reflections between surfaces, thereby improving the overall visual quality of the system. Besides the CAVE structure is equipped with external cladding panels that prevent ambient light from interfering with the projection system, thereby improving image quality and immersion.

Projection System

The visual content of the CAVE is generated through a system of four high-performance projectors, specifically Barco UDM-4K15 laser projectors, based on 3-chip DLP technology, shown in Figure 5. These kinds of projectors offer native resolution up to WQXGA (2560×1600), support for UHD 4K (pixel-shifted), brightness of approximately 14,000–15,000 lumens, contrast ratio of 2200:1, operational lifetime of up to 20,000 hours.



Figure 5: Barco UDM-4K15 laser projector used in the CAVE system

The projectors are connected via fiber optic cables and are precisely calibrated to ensure seamless image alignment across all projection surfaces. This calibration process is essential to avoid distortions or discontinuities at the edges of the screens. The stereoscopic visualization permits users to perceive depth through synchronized rendering of images for each eye. The arrangement of the projectors follows a multi-directional projection geometry designed to maximize visual continuity and immersive coverage across the different surfaces of the environment. Figure 6 presents the projection and mirror arrangement used within the CAVE infrastructure. The optical path allows the projected images to be accurately distributed across the display surfaces, ensuring geometric consistency, correct scaling, and coherent

visualization of the virtual environment. Each projector is positioned externally with a specific projection angle to cover individual walls while minimizing visual overlap and distortion. The top and side views of the system emphasize the spatial configuration required to ensure synchronized stereoscopic visualization across multiple projection planes. This method consents the immersive environment to maintain consistent perspective rendering while supporting user movement inside the CAVE space. The geometric calibration between projectors preserves depth perception, spatial realism, and accurate immersive interaction. Moreover, the external placement of the projectors contributes to reducing physical obstructions within the immersive area, allowing users to move more naturally inside the virtual environment without interfering with the projection system itself.

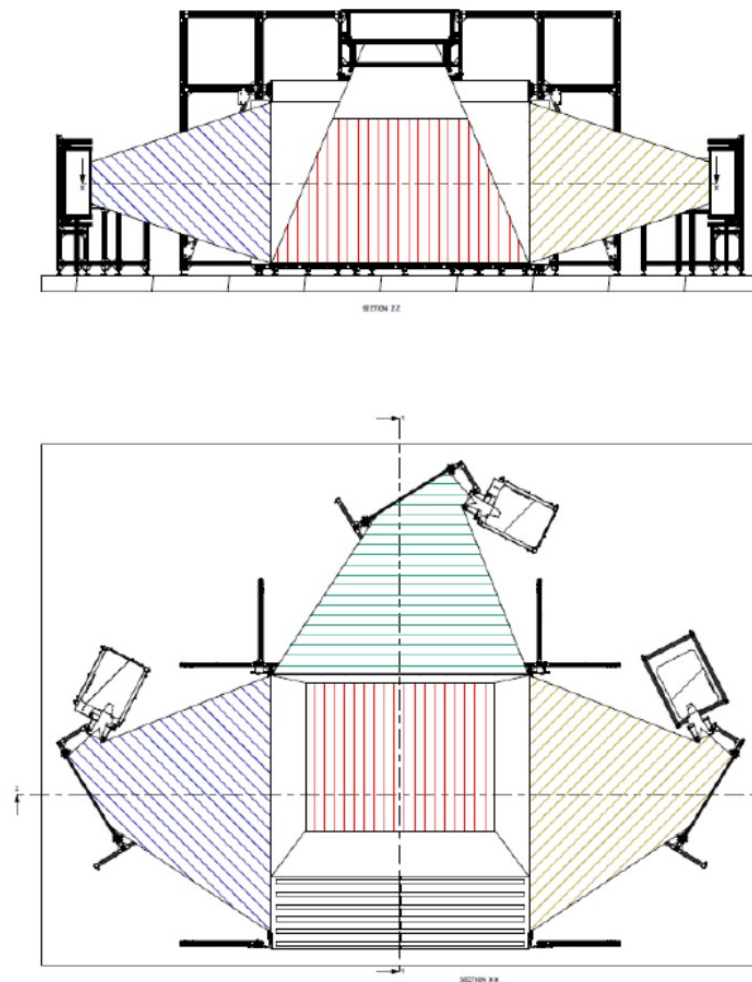


Figure 6: Top and side view of the CAVE projection geometry and multi-projector spatial configuration

Computing Cluster

To manage the rendering of complex virtual environments across multiple screens, the CAVE system is equipped with a cluster of four high-performance workstations (HP Z4 G4). Each workstation is equipped with Intel Xeon processors, supports up to 128 GB of RAM, integrates NVIDIA Quadro RTX 8000 GPUs with 48 GB of VRAM, and utilizes SSD storage systems to ensure high-performance real-time rendering and data processing. Figure 7 presents the main hardware elements supporting the CAVE system, namely the HP Z4 G4 workstation, the HP Z24i G2 monitor, and the APC NetShelter SV 42U rack. These components constitute the core computational infrastructure responsible for rendering, visualization, and system management, operating in a synchronized cluster configuration and enabling real-time rendering of high-resolution graphics across multiple projection surfaces.



Figure 7: High performance workstation cluster and infrastructure components used for real-time rendering and synchronization within the CAVE system

Tracking and interaction System

The CAVE system is equipped with a professional optical motion tracking system based on OptiTrack technology, designed to capture user movements with high precision and low latency. The system includes a set of eight PrimeX22 cameras, each featuring a resolution of 2.2 megapixels and capable of operating at high frame rates, ensuring accurate tracking of both position and orientation. The cameras are arranged around the CAVE structure and connected through an Ethernet-based network, which allows both power supply and data transmission. The tracking system operates with a latency of approximately 2.8 milliseconds, enabling real-time responsiveness that is essential for maintaining a coherent and immersive experience. Calibration of the tracking system is performed using dedicated tools and software, allowing

for precise alignment of the tracking space with the virtual environment. The system supports both rigid body tracking and full-body motion capture. Interaction with the virtual environment is enhanced through the use of input devices such as wireless controllers. In particular, the system includes multiple Xbox One controllers equipped with optical markers, allowing their position to be tracked within the CAVE. As well, stereoscopic visualization is achieved with active 3D glasses synchronized via radio frequency. These devices ensure proper depth perception and are integrated with the tracking system to maintain visual consistency with the user's viewpoint.

Audio System

The CAVE system is complemented by a surround audio system designed to enhance immersion through spatial sound reproduction. As shown in Figure 8, the setup is based on a 5.1-channel configuration, specifically the Logitech Z906 system, which delivers a total power output of 500 watts. A subwoofer and multiple satellite speakers are positioned around the CAVE environment, allowing for directional audio cues that correspond to events within the virtual scene. This contributes to a more realistic and engaging experience, particularly in scenarios where auditory feedback plays a role in user perception and decision-making. The integration of audio with visual and interactive components is essential for creating a coherent multisensory experience. In immersive environments, sound can significantly influence emotional responses and situational awareness, making it a relevant component in experimental setups focused on human.



Figure 8: Surround audio system integrated into the CAVE environment

2.2.2 Software

Software Architecture

Figure 9 presents a conceptual overview of the software architecture adopted by the CAVE system. The diagram illustrates the interaction between input systems, application logic, rendering nodes, projection surfaces, and supporting infrastructure components involved in the generation of the immersive experience. Unlike standard virtual reality systems, which typically rely on a single rendering pipeline, CAVE environments require a distributed and coordinated software structure capable of managing multiple projection surfaces simultaneously.

Rendering and Visualization Pipeline

The software layer serves as the central platform for the creation, execution, and management of immersive virtual environments. Developers can design and configure virtual scenarios using standard three-dimensional content creation workflows, while the rendering system is responsible for distributing visual information across multiple projection surfaces. The rendering pipeline is specifically configured to support multi-screen visualization, allowing the virtual scene to be rendered simultaneously on different projection surfaces while maintaining visual continuity between adjacent displays. Figure 9 illustrates how the rendering cluster

distributes visual information across multiple rendering nodes before synchronizing the output delivered to the projection surfaces of the CAVE environment. The system leverages modern graphics processing technologies and distributed computing resources to support the visualization of complex virtual environments characterized by high levels of detail and real-time responsiveness.

CAVE Management Framework

Multi-screen rendering, synchronization between rendering nodes, calibration of projection surfaces and viewports, stereoscopic visualization, integration of motion-tracking data and management of user input devices are centralized within a unified software layer; the system simplifies the development and deployment of immersive applications while reducing overall architectural complexity. The framework also ensures that all subsystems operate coherently, contributing to a stable and immersive user experience.

Interaction and Input Integration

Motion-tracking systems continuously monitor the position and orientation of users, providing data that are used to dynamically update the visual perspective displayed within the immersive environment. As illustrated in Figure 9, tracking data are transmitted to the application layer and subsequently incorporated into the rendering process, allowing real-time adaptation of the virtual perspective to user movements. Additional input devices can be employed to support navigation, object manipulation, selection tasks, and interaction with virtual elements, a wide variety of interaction can be potentially included depending on the objectives of the application.

Extensibility and Development Support

The adopted architecture has been designed with flexibility and extensibility in mind. The modular organization of the software components facilitates the implementation of custom functionalities, integration of external systems, and adaptation to different application domains. This flexibility consents developers to create specialized immersive scenarios tailored to research, training, industrial visualization, or simulation activities.

System Synchronization and Multi-Node Operation

The software architecture ensures synchronization between the different components of the system, including rendering nodes, tracking systems, and input devices; the cluster-based architecture enables multiple workstations to operate together, with each node responsible for rendering a specific portion of the virtual environment. The software framework coordinates the communication between these nodes, ensuring that all visual outputs remain synchronized and updated in real time. Figure 9 highlights the synchronization mechanism implemented by the master node, which coordinates rendering operations and ensures visual consistency across all projection surfaces within the immersive environment.

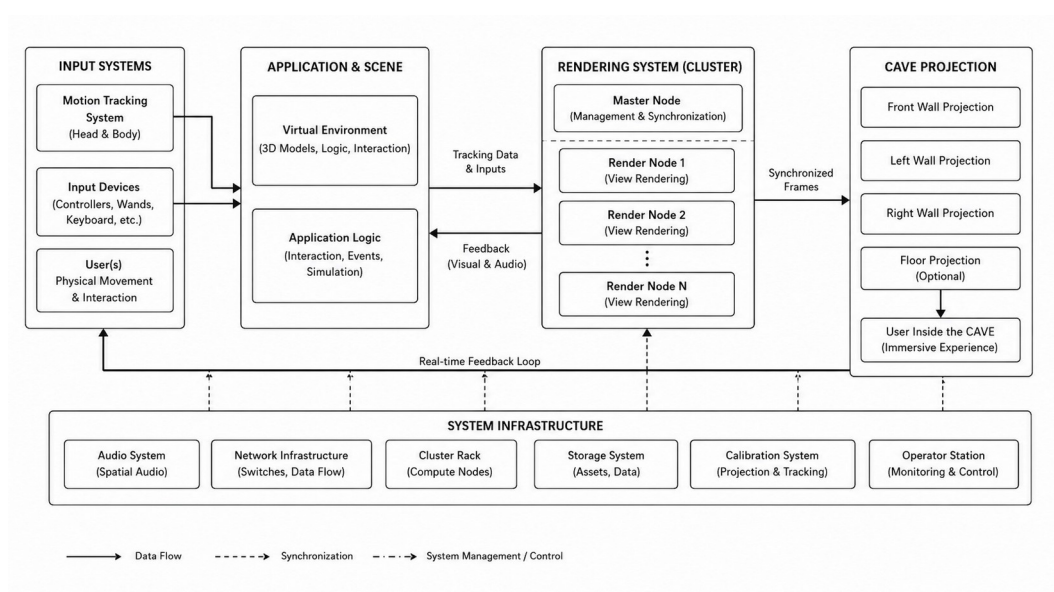


Figure 9: Simplified overview of the CAVE software architecture, showing rendering synchronization, distributed cluster management and multi-screen projection workflow

2.3 Emotional Environment of the Proposed Experiment

The initial stage is intentionally designed as a neutral and task-oriented phase; the participant is required to enter an elevator and complete a sequence of tasks interacting with the elevator interface. More specifically, the user must press elevator buttons following a predefined sequence paying attention to select the correct one. Then, a general knowledge question is presented that must be answered before proceeding further within the scenario. This stage introduces a moderate level of cognitive engagement, establishing a baseline condition prior to the introduction of emotionally significant stimuli. After completing the initial tasks, the participant selects a destination floor within the building; at this point, an unexpected event

happens: a fire breaks out inside the elevator cabin. This event constitutes the critical phase of the experiment and is specifically designed to induce stress, urgency, and heightened emotional arousal. The fire originates in the upper section of the elevator, generating a visually salient and potentially threatening situation. To respond to the emergency, the participant must identify and use a fire extinguisher positioned within the virtual environment, specifically in the lower-left area of the elevator. The extinguisher can be picked up and operated through the handheld controller, allowing the user to actively engage with the emergency scenario. This interaction combines motor activity, rapid decision-making, and emotional response, as participants are required to react promptly to resolve the situation successfully. Once the fire has been extinguished, the elevator resumes operation and reaches the selected floor. The participant then exits the elevator and enters a second virtual environment representing an office setting. This transition introduces a shift from a highly arousing emergency to a more controlled and cognitively oriented context. Within the office environment, the participant interacts with a virtual agent representing a potential employer; four different job contract proposals are presented, each characterized by distinct conditions and benefits. The participant is required to evaluate the available options and select their preferred contract. This phase was specifically designed to investigate decision-making processes preceded by an emotionally intense experience, allowing the observation of how prior stress exposure may influence cognitive evaluation and choice behavior. Following completion of the decision-making task, the participant exits the virtual environment, marking the conclusion of the experimental procedure.

2.4 Comparison with other CAVE Environment in Literature

2.4.1 Overview of Selected Studies

The selected studies analyzed in this work reflect a broad range of applications, including emergency simulations, environmental perception and training scenarios; although these studies differ in their specific objectives, they share several common characteristics. A recurring aspect across the analyzed literature is the use of CAVE or CAVE-like systems for behavioral analysis in scenarios designed to elicit emotional and cognitive responses, allowing researchers to study decision-making processes under stress. Other studies focus on more

neutral or exploratory environments, such as natural landscapes or urban spaces, with the aim of analyzing perception, presence, and user experience. The following section provides a structured analysis of the selected studies, highlighting their main characteristics in terms of experimental design, virtual environment, and observed results.

1)A Study on Evacuation Behavior in Physical and Virtual Reality Experiments – [35]

Context and objective

The study evaluates the suitability of Virtual Reality as a research tool for investigating human evacuation behavior by comparing participants' responses across three experimental settings: a real building, a CAVE system, and a Head-Mounted Display (HMD) environment. It examines whether immersive virtual environments can accurately reproduce the behavioral patterns observed during emergency evacuations, including pre-evacuation activities, route selection, exit choice, waiting behavior, and visual attention.

CAVE Hardware

The experiment employed a four-sided CAVE system composed of three projection walls and a floor with stereoscopic visualization and motion tracking. Participants navigated the virtual environment using a handheld controller while remaining physically stationary inside the immersive space.

Virtual environment and user task

The experiment was conducted in a hotel designed with both emergency staircases and evacuation elevators, replicated also in a virtual environment. Participants were not informed that the study focused on evacuation behavior; they were asked to inspect a hotel room before an unexpected fire alarm initiated the evacuation scenario. Following the alarm, they independently decided how to evacuate the building, choosing between the elevators and staircases while navigating either the real hotel, a CAVE system or an HMD-based virtual replica of the same structure. Both virtual environments faithfully reproduced the building layout,

emergency signage, voice alarm system, and evacuation routes. Researchers collected a range of behavioral measures, including pre-evacuation time, walking trajectories, exit choice, waiting time for elevators, and eye-tracking data related to emergency signage. Participants in the HMD condition also completed post-experiment questionnaires assessing the perceived realism, level of immersion, and overall usability of the virtual environment.

Result and key findings

The findings showed that the HMD-based virtual environment successfully reproduced several key behaviors observed in the real-world experiment, including pre-evacuation time, exit choice and other aspects of the evacuation process. These results support the use of immersive VR as a reliable platform for fire evacuation research. In contrast, the CAVE condition showed greater discrepancies, particularly in exit selection and navigation, which the authors mainly attributed to the controller-based locomotion used to move through the virtual environment. Eye-tracking analyses revealed similar patterns of visual attention toward emergency signage in both the real and HMD conditions. Participants also rated the HMD environment as realistic and moderately immersive. Although some differences remained, particularly in terms of navigation, interaction, and perceived realism, the overall results suggest that immersive virtual reality provides a valid and practical platform for investigating human behavior during emergency evacuations when real-world experimentation is impractical or unsafe. At the same time, the study emphasizes that the characteristics of the adopted VR technology can influence user behavior and should therefore be carefully considered when designing immersive behavioral experiments.



Figure 10: Original illustration of the physical (left) and virtual (right) environment based on the experimental paradigm proposed in [35]

2) Influence of reward learning on visual attention and eye movements in a naturalistic environment: A virtual reality study -[36]

Context and objectives

The study focuses on the analysis of emotional responses and anxiety levels in virtual environments. In Figure 11 is shown a view of a user taking part at the experiment. The main objective is to evaluate how immersive virtual reality can be used to induce and measure stress and anxiety, particularly in controlled experimental conditions.

CAVE hardware

The experiment employed a four-sided CAVE system with stereoscopic projection, optical motion tracking, and integrated eye-tracking capabilities. Participants explored a naturalistic virtual environment using a handheld joystick while the system continuously updated the visual scene according to their head position, enabling immersive and ecologically valid behavioral observation.

Virtual environment and User task

Participants are exposed to virtual scenarios specifically designed to induce anxiety or stress-related reactions; the environment choose is a natural setting. The surrounding vegetation enhances the ecological realism of the virtual environment. During the experiment, participants navigated through a virtual forest while searching for white rabbits and birds that appeared with equal probability on either the left or the right side of the path. Correctly detecting targets appearing on one predetermined side consistently resulted in a higher reward (10 points), whereas correct detections on the opposite side yielded only a lower reward (1 point). Participants were not informed about this difference in the reward structure. This manipulation was designed to examine whether implicit reward learning could unconsciously bias visual attention and eye movements toward the side associated with the greater reward. More specifically, the experiment investigated whether the human attentional system automatically prioritizes spatial locations that gradually acquire higher motivational value through experience.

Results and key findings

The results show that immersive virtual environments provide an effective framework for investigating reward-driven attentional processes under ecologically valid conditions. Over the course of the experiment, participants gradually developed an implicit attentional bias toward the side associated with higher rewards, as reflected in their eye-movement patterns rather than in task accuracy. Notably, this effect emerged even though participants were unaware of the underlying reward contingency, suggesting that reward learning can influence visual exploration without conscious awareness. However, the attentional bias transferred only partially to a different virtual environment and did not influence subsequent spatial decision-making. These findings indicate that the effects of reward learning on visual attention are strongly context-dependent and do not readily generalize across different environments.



Figure 11: Original Illustration of the experimental setup - [36]

3) Driving behavior in immersive Virtual Environments: a study on the role of cognitive workload, sense of presence and simulation sickness in the CAVE laboratory - [37]

Context and Objective

The study investigates driving behavior within an immersive CAVE environment under controlled experimental conditions. It examines how cognitive workload, sense of presence, and simulation sickness influence driving performance during realistic urban traffic scenarios. This approach allows the authors to evaluate the effectiveness of CAVE-based virtual reality as a platform for studying driver behavior and validating immersive driving simulations without exposing participants to real-world risks.

CAVE hardware

The experiment employed an immersive CAVE driving simulator providing a wide field of view and real-time visualization of a virtual urban environment. Participants navigated the simulated road network while interacting with dynamic traffic scenarios, enabling the assessment of driving behavior and human factors such as cognitive workload, sense of presence, and simulation sickness in a controlled immersive setting.

Virtual experiment and User Task

Participants are immersed in a realistic urban environment displayed within a CAVE system. As illustrated in Figure 13, they interact with a driving simulator while navigating a virtual city composed of road segments, intersections, and pedestrian crossings. Throughout the experiment, participants are required to comply with traffic regulations while responding to both expected pedestrian crossings and unexpected jaywalking events.

Result and key findings

The results indicate that CAVE-based virtual reality provides a reliable platform for reproducing realistic driving scenarios and investigating driver behavior under controlled laboratory conditions. Among the psychophysiological variables examined, cognitive workload had the greatest influence on driving performance, whereas simulation sickness exerted a weaker,

although still measurable, effect. In contrast, the sense of presence was not significantly associated with driving performance, suggesting that a higher level of immersion does not necessarily translate into better task execution. The findings support the use of CAVE environments for human factors and road safety research, offering a safe and controlled setting in which driver behavior can be investigated while accounting for the influence of both psychological and physiological factors.



Figure 12: Original illustration of a picture of the experimental set-up (left); the key plan of the road scenario (right) divided in three segments (T) for analysis purposes - [37]

4)Height Simulation in a Virtual Reality CAVE System: Validity of Fear Responses and Effects of an Immersion Manipulation - [38]

Context and Objective

The study examines the use of a CAVE virtual reality system to induce and analyze fear responses associated with acrophobia. It evaluates the ability of the virtual environment to elicit realistic emotional and behavioral reactions to height exposure, while also investigating whether increasing the level of immersion through wind simulation influences both fear responses and the sense of presence. In addition, the study explores the relationship between trait acrophobic anxiety, perceived presence, and emotional responses under controlled experimental conditions.

CAVE Hardware

The experiment was conducted using a five-sided multisensory CAVE system with stereoscopic projection, optical motion tracking, and surround audio. Participants freely explored a virtual height environment while the system combined visual, acoustic, and tactile cues (wind simulation) to investigate fear responses, presence, and avoidance behavior under highly controlled immersive conditions.

Virtual Environment and User Task

The virtual environment reproduced a 50-meter observation tower overlooking a mountainous landscape. Participants climbed the tower, approached the safety railing as closely as they felt comfortable, and completed a series of behavioral tasks while reporting their perceived levels of fear, danger, dizziness, and sense of presence. To examine the effect of immersion, half of the participants experienced an additional wind simulation synchronized with the virtual environment.

Result and Key Findings

The findings show that the CAVE environment successfully elicited fear and avoidance responses that were consistent with participants' levels of acrophobic anxiety. The addition of wind simulation further increased fear responses among participants with higher levels of

height anxiety, although it did not produce a significant change in the perceived sense of presence. In addition, presence emerged as an independent predictor of fear intensity, highlighting the value of CAVE-based virtual environments as a reliable platform for investigating emotional responses under controlled conditions while preserving a high degree of ecological validity.



Figure 13: Original schematic representation of a participant in the 5-sided Cave Automatic Virtual Environment (CAVE) climbing the stairs of the lookout (left) - [38]

5) Pedestrian Behavior in Static and Dynamic Virtual Road Crossing Experiments - [39]

Context and Objective

The study investigates pedestrian road-crossing behavior in an immersive virtual environment, comparing a realistic and dynamic crossing task, in which participants physically walk across a semi-virtual crosswalk, with a traditional static virtual crossing task. The aim is to determine whether a more natural form of interaction influences pedestrians' decision-making during

road crossing. Secondly, the study examines how factors such as vehicle speed, initial vehicle distance, and movement patterns affect crossing decisions within a CAVE-based virtual reality environment.

CAVE Hardware

The experiment employed a CAVE-based pedestrian simulator with stereoscopic projection, motion tracking, and spatialized audio to reproduce realistic urban road-crossing scenarios. Participants interacted with virtual traffic by either making static crossing decisions or physically walking across a semi-virtual crosswalk, enabling the evaluation of pedestrian behavior under controlled yet naturalistic conditions.

Virtual Environment and User Task

Sixty participants took part in the study and were assigned to one of two experimental conditions. In the static condition, participants indicated their decision to cross the road using a mouse, whereas in the dynamic condition they physically walked across a semi-virtual crosswalk. Each participant completed a hundred randomized trials combining different vehicle speeds (20km/h and 30 km/h), initial vehicle distances, and vehicle movement patterns, including constant speed, deceleration, and complete stopping. Realistic visual cues and spatialized audio were synchronized to simulate approaching vehicles, providing a controlled yet immersive setting in which crossing decisions, crossing initiation time, and time-to-passage could be accurately assessed.

Result and Key Finding

The results indicated that the experimental approach, whether static or dynamic, did not significantly influence pedestrians' overall road-crossing decisions. Instead, crossing behavior was primarily determined by vehicle-related factors, with participants showing a greater willingness to cross when vehicles approached at lower speeds and from longer distances. Although individuals in the dynamic condition generally required more time to initiate crossing, the overall decision-making patterns remained consistent across both experimental conditions. These findings suggest that physically walking within an immersive CAVE

environment does not substantially modify pedestrian decision-making, supporting the use of both static and dynamic virtual reality paradigms for investigating road-crossing behavior.



Figure 14: Original illustration of a pedestrian performing the experiment - [39]

6) Immersive insights: evaluating augmented reality interfaces for pedestrians in a CAVE-based experiment - [40]

Context and objective

The study investigates the effectiveness of nine Augmented Reality (AR) interfaces developed to support interactions between pedestrians and automated vehicles (AVs). It evaluates whether the intuitiveness and usability of these interfaces, previously assessed through an online questionnaire, can be replicated in an immersive CAVE-based virtual reality environment. The study also explores how different interface placements—head-locked, infrastructure-locked, and vehicle-locked—together with pedestrians' initial visual attention, influence road-crossing behaviour and the overall usability of the proposed interfaces.

CAVE Hardware

The experiment was conducted using the Highly Immersive Kinematic Experimental Research (HIKER) CAVE simulator, combining multi-surface stereoscopic projection, real-time head tracking, eye tracking, and Unity-based rendering. Participants interacted with virtual traffic scenarios enhanced by augmented reality interfaces, allowing researchers to analyze pedestrian decision-making and visual attention in an ecologically valid immersive environment.

Virtual Environment and User Task

Thirty participants completed 120 road-crossing trials in a CAVE-based pedestrian simulator. In each trial, an automated vehicle either yielded or continued driving, while its intentions were communicated through one of nine Augmented Reality (AR) interfaces or a baseline condition without AR support. The proposed interfaces were grouped into three categories: infrastructure-locked, vehicle-locked, and head-locked. To manipulate visual attention, participants were instructed to fixate on an attention-attractor positioned to the left, center or right before the approaching vehicle entered the scene. They then physically crossed the virtual road whenever they considered it safe to do so. After each trial, participants rated the intuitiveness of the displayed interface, while eye movements, gaze behavior, crossing initiation time, and subjective preferences were continuously recorded throughout the experiment.

Result and Key Findings

The immersive experiment successfully replicated the findings of the previous online study, with intuitiveness ratings showing a very strong correlation across the two experimental settings. Interfaces based on familiar traffic elements, such as the augmented zebra crossing, pedestrian traffic lights, and head-up displays, were consistently perceived as the most intuitive and allowed participants to initiate road crossing more quickly. By contrast, vehicle-locked interfaces were generally less intuitive and were more strongly influenced by participants' initial gaze direction, particularly when their attention was focused away from the

approaching vehicle. Head-locked interfaces, on the other hand, maintained a consistently high level of effectiveness regardless of the initial gaze position, highlighting the importance of interface placement relative to the user's field of view in supporting safe pedestrian decision-making within immersive environments.



Figure 15: Original illustration of a participant standing on the blue marker and looking at the cyan attention-attractor circle, which is displayed in the center position - [40]

7) Analysis of Physiological Responses to a Social Situation in an Immersive Virtual Environment - [41]

Context and Objective

The study investigates whether physiological responses can serve as objective indicators of presence in immersive virtual environments. It examines changes in heart rate (HR), heart rate variability (HRV), and galvanic skin response (GSR) during two types of events within a virtual bar scenario: (1) experimentally induced breaks in presence, generated through brief whiteouts of the virtual environment, and (2) social interactions initiated by virtual characters. In addition, the study evaluates whether these physiological responses vary according to participants' levels of social anxiety.

CAVE Hardware

The experiment was conducted using a four-sided CAVE-like immersive virtual reality system with stereoscopic projection and real-time head tracking.

Virtual Environment and User Task

Twenty participants explored an immersive CAVE-based virtual environment representing a bar populated by five interactive virtual characters. The experimental protocol comprised three stages: a baseline session, a training session to familiarize participants with the virtual environment, and a five-minute experimental session. During the experiment, participants freely explored the virtual bar while occasionally interacting with the virtual characters, who initiated brief social exchanges. At regular intervals, four breaks in presence were introduced by replacing the virtual scene with a white screen for two seconds. Throughout the session, electrocardiogram and galvanic skin response signals were continuously recorded to assess heart rate, heart rate variability, event-related cardiac responses, and electrodermal activity. Participants also completed questionnaires collecting demographic information and assessing their level of social anxiety.

Result and Key Findings

The experimental session was associated with lower heart rate and higher heart rate variability than the training session, suggesting that participants became progressively more relaxed as they adapted to the immersive social environment. Individuals with higher levels of social anxiety showed consistently higher heart rates and lower heart rate variability than those with lower anxiety levels. Interactions with speaking virtual characters produced a modest increase in heart rate, whereas breaks in presence triggered a clear physiological response, characterized by a reduction in heart rate followed by an increase in galvanic skin response approximately three seconds after each whiteout. In addition, wavelet analysis of the GSR signals identified breaks in presence with good accuracy, supporting the use of physiological measures as objective indicators of disruptions in presence within immersive virtual environments.

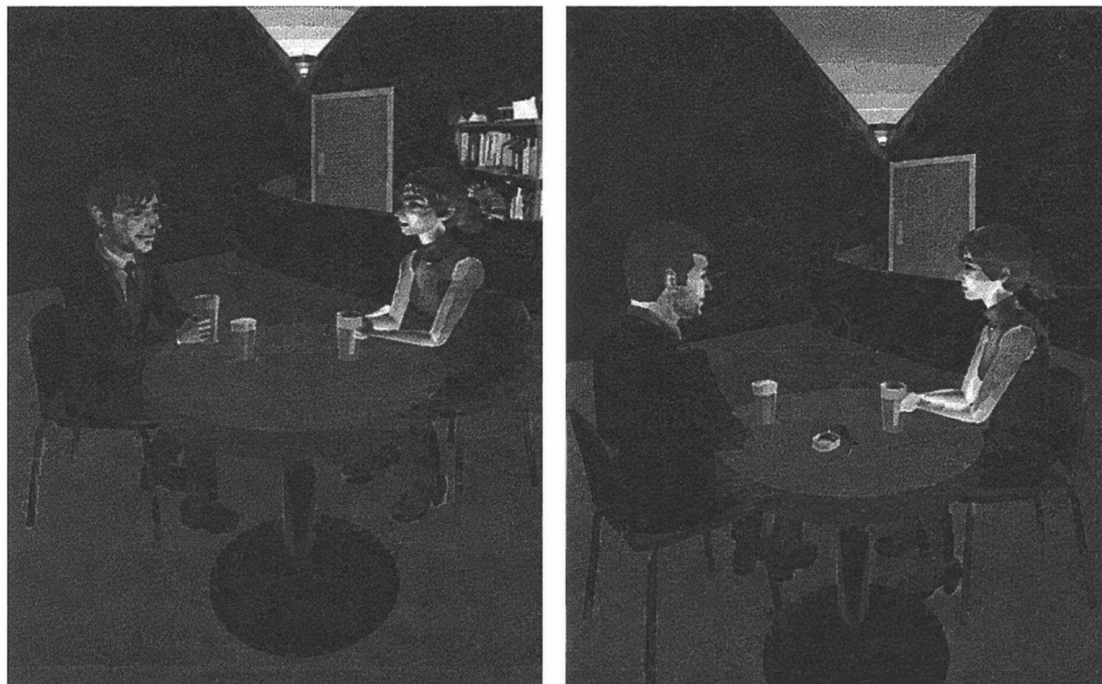


Figure 16: The bar scene – [41]

8) The Nature of Reality: Human Stress Recovery during Exposure to Biodiverse, Multisensory Virtual Environments - [42]

Context and Objective

The study investigates whether immersive virtual environments representing different levels of biodiversity can promote recovery from experimentally induced stress. To address this question, the authors examined several aspects of the restorative experience. First, they evaluated whether an immersive virtual Trier Social Stress Test effectively induced psychological stress. They then compared stress recovery between urban and natural virtual environments, assessed the influence of different levels of biodiversity on recovery, and examined whether participants accurately perceived variations in biodiversity. In the end, the study investigated whether enriching the virtual environments with auditory and olfactory stimuli enhanced both stress recovery and the perception of biodiversity.

CAVE Hardware

The experiment employed an immersive CAVE-based virtual reality system with large-scale stereoscopic projection to present realistic urban and natural environments. Participants experienced multisensory virtual scenes combining visual, auditory, and olfactory stimuli while physiological and self-reported measures were collected to evaluate stress recovery and emotional well-being under controlled immersive conditions.

Virtual Environment and User Task

The study involved 52 healthy adult participants, who were randomly assigned to one of five immersive virtual environments: an urban setting, a natural environment with low biodiversity, a natural environment with moderate biodiversity, a multisensory natural environment with high biodiversity, or a visual-only natural environment with high biodiversity. Stress was induced using an immersive virtual adaptation of the Trier Social Stress Test, during which participants delivered a five-minute speech and completed a mental arithmetic task in front of a 360° virtual audience. Following the stress induction, participants spent five minutes immersed in their assigned virtual environment to evaluate the recovery process. The environments consisted of 360° videos viewed through an Oculus Rift headset and differed in

vegetation complexity, structural diversity, bird sounds, and the presence of natural scents. Throughout the experiment, heart rate was continuously monitored, while visual analogue scales were administered before and after each experimental phase to assess perceived stress, anxiety, insecurity, calmness, and happiness.

Result and Key Findings

The Trier Social Stress Test successfully induced stress, producing significant increases in heart rate, perceived stress, anxiety, and insecurity, together with significant decreases in calmness and happiness. Recovery was generally poorest in the urban virtual environment, whereas natural environments promoted better psychological recovery. Interestingly, the low-biodiversity natural environment produced the greatest improvements in several outcomes, including perceived stress, anxiety, happiness, and heart rate recovery, while the moderate-biodiversity environment consistently showed the weakest restorative effects among the natural settings. The relationship between biodiversity and stress recovery was therefore not linear. Multisensory stimulation (combining visual, auditory, and olfactory cues) further enhanced recovery, with participants showing significantly greater reductions in anxiety compared with the visual-only version of the same high-biodiversity environment. Although participants clearly distinguished urban from natural environments, their ability to discriminate between different biodiversity levels was limited. The findings indicate that immersive, multisensory virtual nature can effectively facilitate stress recovery, but increasing biodiversity alone does not necessarily lead to proportionally greater restorative benefits.



Figure 17: Original illustration of the four immersive virtual environments used in the experiment - [42]

9) Authentic Fear Responses in Virtual Reality: A Mobile EEG Study on Affective, Behavioral and Electrophysiological Correlates of Fear – [43]

Context and objective

The study investigates whether virtual reality (VR) can elicit fear responses comparable to those experienced in real-life situations by combining immersive virtual environments, realistic physical interaction, and mobile electroencephalography (EEG). To address this question, participants were exposed to a threatening virtual cave designed to evoke emotional reactions while their affective, behavioral, psychophysiological, and electrophysiological responses were assessed. The study also examined whether frontal alpha asymmetry (FAA), an EEG marker commonly associated with approach and avoidance motivation, reflects natural fear-related behaviors under ecologically valid experimental conditions.

CAVE Hardware and Software

The experiment employed a mixed reality immersive setup combining a wireless HTC Vive Pro headset with a life-size physical replica of a virtual cave. Participants physically explored the environment while interacting with synchronized virtual and haptic elements, and mobile EEG recordings were collected to investigate authentic fear responses, behavioral reactions, and electrophysiological correlates under highly immersive conditions.

Virtual Environment and User Task

The study involved 81 healthy adult participants, who were randomly assigned to either a fear-inducing virtual cave ($n = 54$) or a neutral virtual cave ($n = 27$). Using an HTC Vive Pro wireless head-mounted display, participants physically walked through a life-sized replica of the virtual environment, allowing them to naturally interact with walls and objects through tactile feedback. The fear-inducing environment included threatening stimuli such as a mutilated corpse, crying sounds, and an approaching werewolf, whereas the neutral environment presented non-threatening elements, including a tree trunk, wind sounds, and a sheep. Throughout the experiment, participants wore a mobile 32-channel electroencephalography (EEG) system to record frontal alpha asymmetry (FAA) and a three-channel electrocardiogram (ECG) to assess heart rate variability (HRV). They also completed questionnaires evaluating

affect, anxiety, presence, and motivational state before and after the virtual reality experience. Behavioral measures, including exploration time, movement patterns, and avoidance responses, were collected through video analysis, enabling the researchers to classify participants as either “hesitating” or “hastening” according to their reactions to the virtual threat.

Result and Key Findings

The immersive virtual environment successfully elicited strong and realistic fear responses. Compared with participants in the neutral condition, those exposed to the threatening cave reported higher levels of negative affect, greater fear, and a stronger desire to leave the environment. Their behavior was equally consistent with a fear response: participants moved more cautiously, verbally expressed fear, and typically either hesitated or rapidly advanced to avoid the approaching werewolf. Independent observers were also able to reliably distinguish different levels of fear based solely on participants’ behavior, further supporting the ecological realism of the immersive experience. In contrast, the physiological findings were less conclusive. Heart rate variability (HRV) did not differ significantly between the two experimental groups, while frontal alpha asymmetry (FAA) showed significant differences only during two specific phases of the virtual experience. The observed FAA patterns were not consistently aligned with theoretical models associating greater left frontal activity with approach behavior and greater right frontal activity with avoidance. The results indicate that immersive virtual reality can successfully reproduce realistic emotional and behavioral responses to fear. At the same time, they suggest that electrophysiological markers derived from controlled laboratory paradigms, such as FAA, may not fully capture the complexity of fear-related behavior in ecologically valid immersive environments.

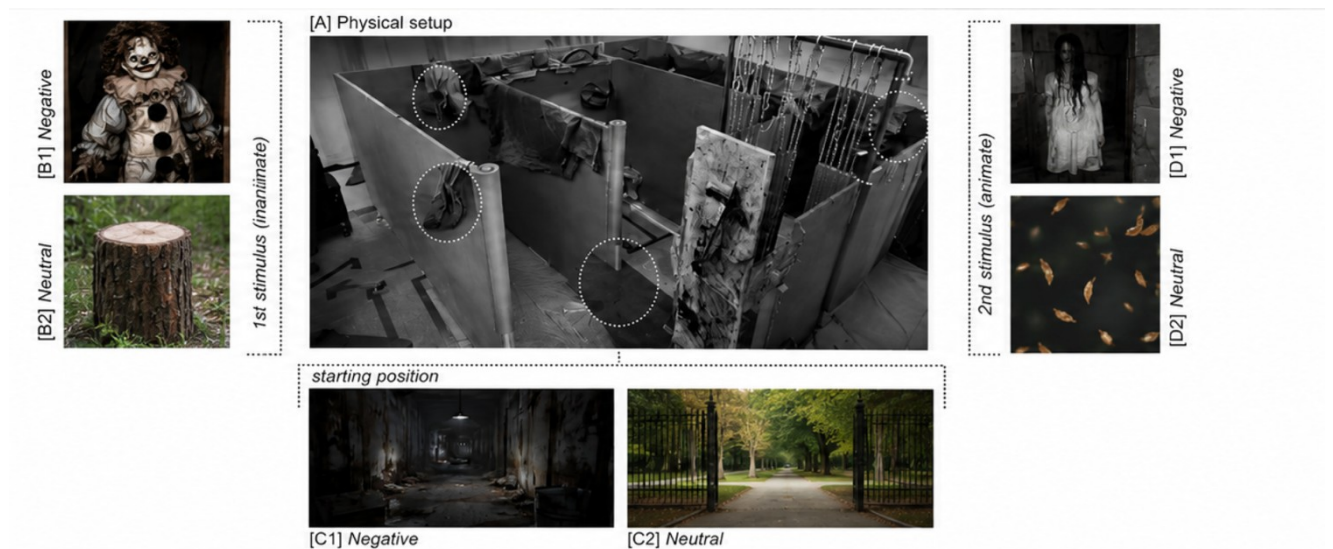


Figure 18: Original illustration of the (physical) cave and respective stimuli per condition - [43]

2.4.2 Classification of Emotional Environments Found in Literature

Although each study presents specific characteristics, it is possible to identify recurring patterns in the design of virtual scenarios. These patterns allow for a structured classification of emotional environments, which provides a useful framework for positioning the proposed experiment within the broader context of the literature. The resulting classification is summarized in Table 2, which groups the reviewed studies according to their primary research objectives and the characteristics of the immersive environments adopted.

High-Risk and Emergency Environments

The first and most prominent category includes environments designed to simulate emergency situations, hazardous conditions, or threatening scenarios. As summarized in Table 2, studies such as [35], [36], [38], [40], [41], [43] are within this group. These studies fall within the broader category of emotion-oriented environments, where immersive scenarios are specifically designed to elicit stress, anxiety, fear, and other emotionally significant responses. Environments like this are characterized by the presence of immediate threats, dynamic events, uncertainty, and time pressure, all of which are intended to induce strong emotional responses, particularly stress, anxiety, fear, and urgency. Emotional activation is primarily generated by external stimuli, including visual cues such as fire, smoke, heights, or hazardous situations, as well as auditory signals such as alarms and warning messages. Consequently, these environments are particularly effective in eliciting high levels of arousal and activating decision-making processes under pressure.

Training-Oriented and Task-Based Environments

A second category includes environments designed for training purposes, skill acquisition, procedural learning, or structured task execution. Representative studies include [37], [39]. According to the classification presented in Table 2, these environments primarily focus on performance improvement, procedural learning, situational awareness and skill acquisition

through immersive task execution. In these environments, emotional responses are not the primary objective but rather emerge as secondary effects of task complexity, performance demands and user engagement. Users are required to complete predefined activities within controlled conditions, often involving procedural tasks, professional training or operational simulations. Emotional responses are therefore influenced by factors such as cognitive workload, perceived competence, task difficulty, and interaction complexity. These environments generally produce moderate levels of emotional activation associated with engagement, satisfaction, frustration, or performance-related stress. Their primary value lies in the analysis of learning processes, usability, performance, situational awareness, and human-computer interaction.

Environmental and Perceptual Experience Environments

The third category includes environments designed to investigate the relationship between environmental characteristics and emotional responses [42]. These environments are typically less task-oriented and instead focus on perception, exploration, and subjective experience. Participants are exposed to different virtual settings, including natural landscapes, biophilic environments, architectural spaces and urban scenarios. Emotional responses are influenced by environmental variables such as lighting conditions, spatial layout, visual realism, environmental complexity and multisensory stimulation. Such environments are particularly useful for investigating valence, emotional restoration, stress recovery, well-being, and low-to-moderate levels of arousal.

Social and Collaborative Environments

A fourth category includes environments specifically designed to investigate social interaction, collaboration, communication and collective behavior emphasizing interpersonal teamwork and collaborative decision-making. Emotional responses emerge from social dynamics rather than from environmental threats or task demands. Such environments are particularly valuable for studying social presence, communication patterns, group behavior, cooperation and interpersonal relationships within immersive virtual settings.

Mixed and Multi-Phase Environments (Proposed Approach)

The environment developed in the study can be classified as a hybrid or multi-phase environment, combining elements from several of the categories described above. The initial phase, involving structured tasks within the elevator, aligns with training-oriented environments because it introduces cognitive workload and requires active user interaction. The subsequent fire event clearly belongs to the category of high-risk environments, as it introduces an unexpected and emotionally intense emergency stimulus. The office scenario represents a decision-making context in which participants must evaluate alternatives and make choices under the influence of prior emotional activation. This combination of phases enables the observation of emotional dynamics over time and facilitates the analysis of interactions between different types of emotional and cognitive stimuli. It provides an opportunity to investigate how a high-arousal event may influence subsequent cognitive processes, including judgment, risk perception, and decision-making behavior, as the project proposed by the CAVE of Polytechnic of Turin

Table 2: Classification of immersive virtual environments based on their primary research objective and representative studies identified in the reviewed literature.

Category	Primary Objective	Example Studies
Emotion-Oriented Environments	Investigate emotional, cognitive, and behavioral responses to immersive stimuli, including stress, anxiety, fear, emotional engagement, and psychological well-being.	[35], [36], [38], [40], [41], [43]
Training-Oriented Environments	Improve performance, learning, procedural execution, situational awareness, and collaborative skills through immersive simulation and task-based activities.	[37], [39]
Environmental and Perceptual Experience Environments	Investigate how environmental characteristics, spatial configurations, and perceptual features influence users' emotional states, well-being, perception, and subjective experience within immersive virtual environments.	[42]

3. Questionnaires and Measurement Tools in VR/CAVE

3.1 Measuring User Experience in Immersive Environments

User experience within immersive virtual environments can be regarded as a complex and multidimensional phenomenon that includes emotional, cognitive, perceptual and behavioral aspects. In comparison with conventional human-computer interaction settings, immersive environments involve a considerably greater degree of sensory involvement and spatial participation; that is the reason why the evaluation of user experience cannot be restricted exclusively to usability or task performance but must also take into account a wider set of dimensions, including emotional reactions, sense of presence, degree of immersion and perceived control within the environment [44]. Emotional responses are generally described along continuous dimensions, mainly valence arousal and dominance [45], [46] [47]. Within interactive virtual scenarios, users are expected to complete tasks, react to unforeseen events and make decisions capable of influencing the progression of the experience, implicating mental effort to react to the environment that increases the cognitive demand. Excessive cognitive demand may negatively influence performance and increase stress, whereas insufficient mental stimulation may decrease engagement and attentional focus. For this reason, cognitive workload is frequently regulated modifying the setting of the experiment [48] [49]. Usability, which refers to the ease with which a user interacts with the system, also influences the overall user experience. Inadequate usability may adversely affect emotional responses by producing frustration, uncertainty, or stress, potentially compromising the objectives of the experiment [50], [51]. User experience assessment requires the integration of multiple methodological strategies. These approaches generally include subjective measures, such as self-report questionnaires with objective indicators, including behavioral information and physiological measurements. Questionnaires assume a particularly relevant role because they enable participants to directly communicate their perceptions and experiences across different dimensions. In the subsequent sections of this thesis, we will review the most widely used questionnaires in the literature and outline the dimensions they assess. Finally, we will identify their key indicators and discuss their utility in evaluating the proposed experiment.

3.2 Emotional Assessment Questionnaires

These instruments allow researchers to capture both general affective dimensions and more specific psychological reactions elicited by virtual stimuli. The following sections examine these

approaches in greater detail, discussing their theoretical foundations, measurement methodologies, and applicability within immersive virtual reality research.

3.2.1 Valence, Arousal and Dominance

Within this framework, valence refers to the positive or negative quality associated with an emotional state, whereas arousal describes the level of psychological activation, ranging from calm or relaxed conditions to highly excited states. Dominance, when considered, reflects the extent to which users perceive themselves as being in control of the situation or environment. These emotional dimensions are commonly assessed through validated instruments such as the Self-Assessment Manikin (SAM). As shown in Figure 19, this tool provides a graphical and language-independent representation of emotional states, enabling participants to report their feelings intuitively and efficiently [45]. It is particularly suitable for immersive virtual environments because it minimizes interruptions during the experience and facilitates rapid emotional assessment.

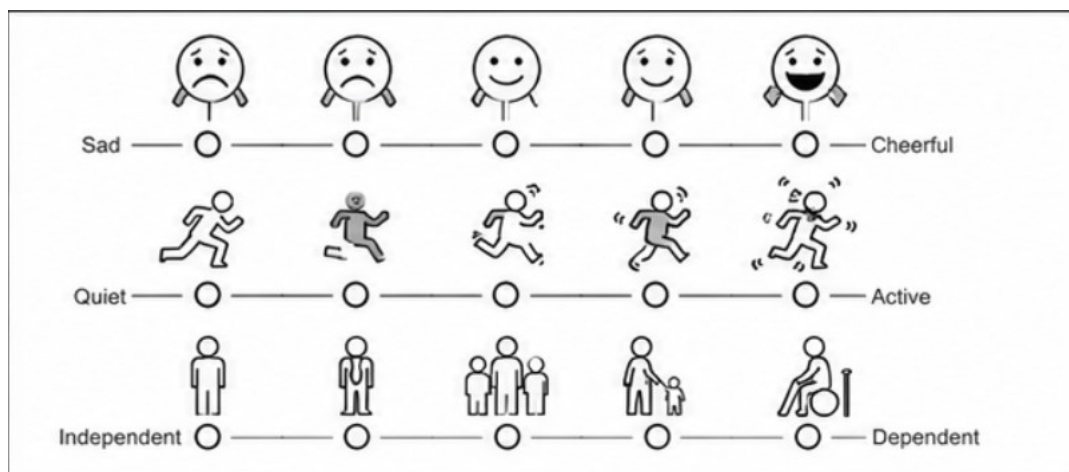


Figure 19: Visual representation of the Self Assessment manikin - [45]

Another instrument is the Visual Analogue Scale (VAS), frequently employed to measure dimensions such as valence and arousal [52]. Figure 20 shows that the VAS is based on a continuous scale, generally ranging from low to high intensity, on which users indicate their perceived emotional state. Due to its simplicity and flexibility, this approach is especially appropriate for repeated measurements collected throughout different stages of an experiment.

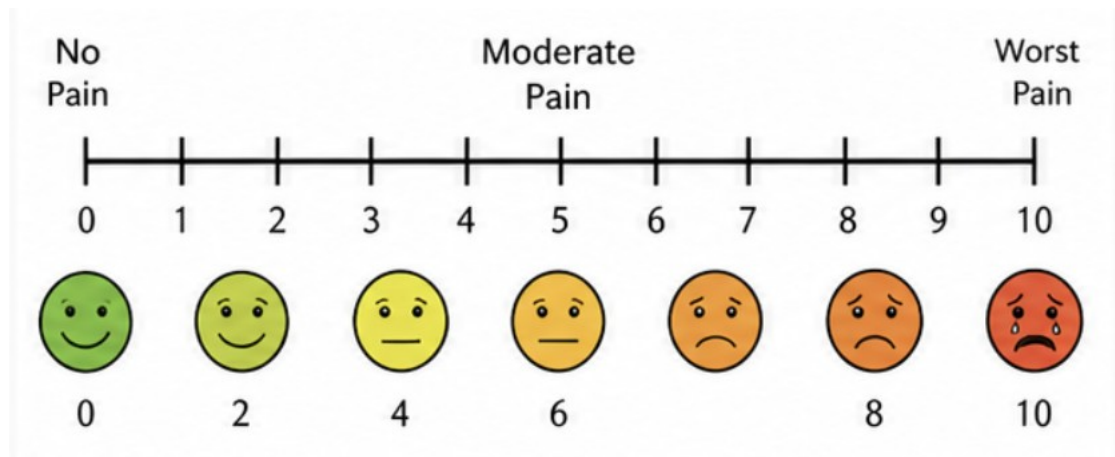


Figure 20: Representation of the Visual Analogue Scale - [52]

More recent methods for emotional assessment include emoji-based grids and visual scales, which provide intuitive alternatives for capturing users' emotional responses. These approaches are particularly useful in immersive contexts where rapid and minimally intrusive evaluation procedures are required [44], [46].

3.2.2 Stress and Anxiety

Stress can generally be described as a psychological and physiological response to external pressures or demanding situations, whereas anxiety is more commonly associated with the anticipation of potential threats or negative outcomes [53]. Within virtual environments, these emotional states may be elicited by environmental stimuli, task complexity, time pressure, or unexpected events occurring during the experience. One of the most widely adopted instruments for the assessment of anxiety is the State-Trait Anxiety Inventory (STAI). As illustrated in the Figure 21, the section contains questions pertaining to stress, each assessed using four response categories: 'not at all,' 'somewhat,' 'moderately,' and 'very much' [54].

	Not at all	Somewhat	Moderately	Very much
1. I feel calm	☐	☐	☐	☐
2. I am tense	☐	☐	☐	☐
3. I feel upset	☐	☐	☐	☐
4. I am relaxed	☐	☐	☐	☐
5. I am content	☐	☐	☐	☐
6. I am worried	☐	☐	☐	☐

Figure 21: Visual Representation of the STAI - [54]

. The evaluation of stress and anxiety is especially important within the proposed experimental scenario, in which the fire event is intentionally designed to elicit a strong emotional reaction. Measuring these dimensions makes it possible to analyze how participants respond to critical situations and how such emotional responses may subsequently influence behavior, performance, and decision-making processes.

3.3 Cognitive Assessment Questionnaires

Within virtual reality research, cognitive assessment commonly focuses on constructs such as cognitive workload and situational awareness. Their relevance becomes particularly evident in scenarios where users are required to process information, make decisions, and react to unexpected events in real time.

3.3.1 Cognitive Workload

Cognitive workload can be defined as the amount of mental effort required to perform a specific task. High levels of cognitive workload are generally associated with increased stress, reduced performance, and a higher probability of errors. Conversely, excessively low workload

may lead to reduced engagement and loss of attention. For this reason, maintaining an appropriate balance in cognitive demand is essential not only for usability, but also for the overall validity and reliability of the experimental process. One of the most widely adopted instruments for measuring cognitive workload is the NASA Task Load Index (NASA-TLX), that is described in Figure 22. This questionnaire evaluates workload across six different dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration [48], [55]. Participants are required to rate each dimension, allowing researchers to obtain a comprehensive assessment of perceived workload during task execution.

Item	Endpoints	Description
Mental demand	1 - 10 Low / High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical demand	1 - 10 Low / High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal demand	1 - 10 Low / High	How much time pressure did you feel due to the rate or pace at which the tasks occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	1 - 10 Good / Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	1 - 10 Low / High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration level	1 - 10 Low / High	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Figure 22: Visual representation of the NASA-TLX questionnaire - [48]

In virtual reality research, simplified versions of the instrument, such as the Raw TLX (RTLX) or the SIM-TLX, are frequently employed to reduce complexity while preserving measurement reliability. These versions are particularly suitable for immersive environments, where repeated evaluations may be necessary throughout different phases of the experiment.

3.3.2 Situation Awareness

Situational awareness refers to the individual's ability to perceive, interpret and anticipate elements within a dynamic environment. It is generally conceptualized as a process composed of three main levels: the first level concerns perception of relevant elements within the

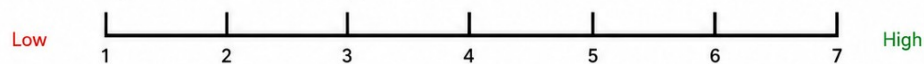
environment, the second regards the comprehension of their meaning and significance and the last analyzes the projection of possible future states. In immersive systems such as CAVE environments, several factors can influence situational awareness, including visual clarity, spatial organization, interaction design, and the presence of dynamic events. The Situation Awareness Rating Technique (SART) is one of the most widely adopted questionnaires in this field; its structure is illustrated in Figure 23. It evaluates different dimensions of awareness, including attentional demand, attentional supply, and understanding of the current situation [56]. The instrument provides a subjective measure of how effectively users perceive, process, and manage information within the virtual environment.

SART – Situation Awareness Rating Technique

For each dimension, please indicate your level of situation awareness by marking a point on the scale that best represents your experience.

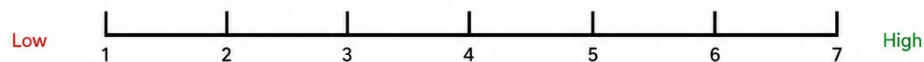
Understanding

How well do you understand what is happening in the situation?



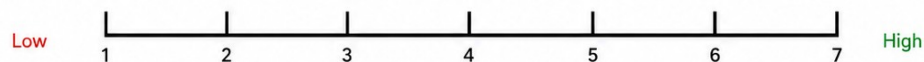
Demand

How much mental processing activity is required to understand the situation?



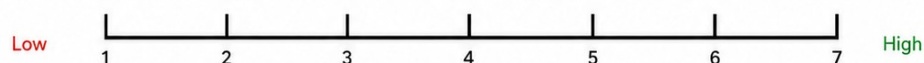
Supply

How much mental processing activity are you currently supplying?



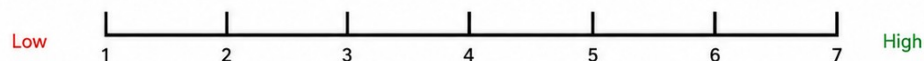
Attention Allocation

How well can you allocate your attention to the different aspects of the situation?



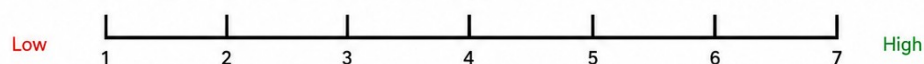
Information Quantity

How much information is available to you?



Information Quality

How valid and reliable is the information available to you?



Familiarity

How familiar are you with the situation?

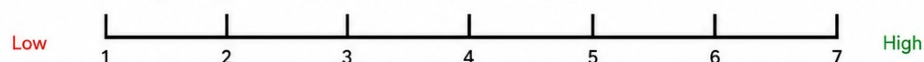


Figure 23: Visual representation of the SART questionnaire - [56]

In addition to SART, situational awareness can also be assessed indirectly through performance-based indicators or in combination with other questionnaires, such as NASA-TLX. This relationship is particularly relevant because cognitive workload and situational awareness are often strongly interconnected.

3.4 Immersion and Presence Questionnaires

The two other dimensions that should be analyzed in the context of this study are immersion and presence. Immersion usually refers to the objective technological capacity of a virtual environment to surround the user with virtual stimuli while presence relates to the psychological dimension of user experience, commonly described as the subjective sensation of “being there”. In this connection, it is useful to consider instruments such as the Presence Questionnaire (PQ), the Igroup Presence Questionnaire (IPQ) and the Multimodal Presence Scale (MPS). The Presence Questionnaire (PQ) is mostly concerned with features of the immersive experience as well as the technical and interaction-related factors that can affect the user’s sense of presence [3]. More specifically, it measures factors such as the level of sensory fidelity, environmental responsiveness, and the user’s control over the virtual world. It is shown in Figure 24. As a simplified and more psychologically oriented version of the previous test, the Igroup Presence Questionnaire (IPQ) was developed later [57].

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

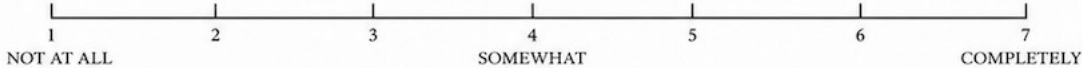
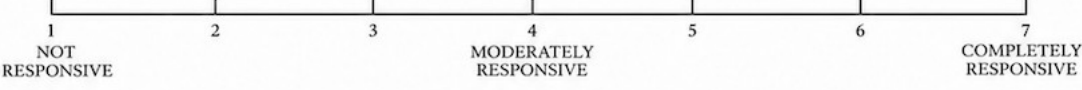
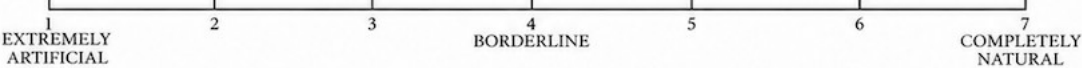
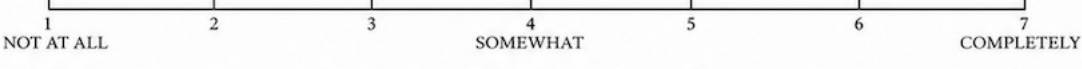
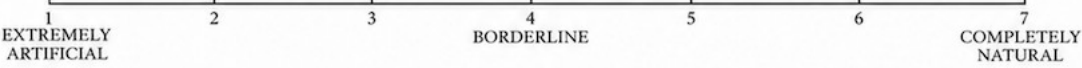
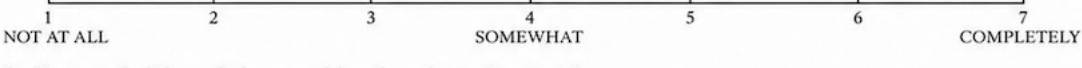
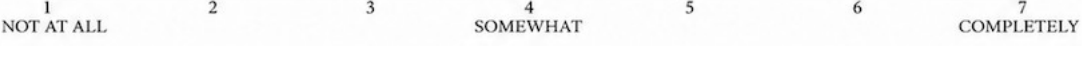
1. How much were you able to control events?

2. How responsive was the environment to actions that you initiated (or performed)?

3. How natural did your interactions with the environment seem?

4. How much did the visual aspects of the environment involve you?

5. How natural was the mechanism which controlled movement through the environment?

6. How much did you feel surrounded by the environment?

7. How much did you feel you could explore the environment?


Figure 24: Visual representation of the Presence Questionnaire - [3]

The Multimodal Presence Scale, illustrated in Figure 25, extends this assessment by distinguishing between physical presence, social presence, and self-presence, providing a more comprehensive representation of the user's experience [58].

Avatar Body-Connectedness

1.	When using the virtual environment, how much do you feel your avatar is a part of your body?
2.	When using your avatar, to what extent do you feel like your arm is elongated into the virtual environment through your avatar?
3.	When using your avatar, to what extent do you feel like you can reach into the virtual environment through your avatar?
4.	When using the virtual environment, how much do you feel like your avatar is an extension of your body within the game/virtual environment?
5.	When using the virtual environment, to what extent do you feel like your hand is inside of the game/virtual environment?

Avatar Identity-Expressiveness

1.	To what extent is your avatar's gender related to some aspect of your personal identity?
2.	To what extent is your avatar's race related to some aspect of your personal identity?
3.	To what extent is your avatar's clothing related to some aspect of your personal identity?
4.	To what extent does your avatar's profile info represent some aspect of your personal identity?
5.	To what extent does your avatar's name represent some aspect of your personal identity?
6.	To what extent is your avatar's appearance related to some aspect of your personal identity?

Figure 25: Visual representation of the Multimodal Presence Scale - [58]

3.5 Usability and User Experience Questionnaires

Usability and User Experience (UX) determine the behavior of the subjects in the virtual world and their interpretation of it. Usability is a complex of elements related both to design and modality of interaction with the system, while User Experience includes emotional and psychological factors involved in using the technology. Different tools can be used for assessing different features of UX and Usability. Usability can be defined as the degree to which a system enables users to complete their tasks efficiently, effectively, and satisfactorily. Issues in

immersive environments may arise from complex interaction processes, inconsistent feedback or inadequate interface design. Such factors can negatively affect user performance and introduce confounding variables into experimental settings [59]. User experience, however, encompasses a broader set of dimensions that involve not only pragmatic characteristics of the system but also emotional responses, engagement and overall satisfaction. The most widely used measurement tool is the System Usability Scale (SUS) [50]. As shown in Figure , this questionnaire consists of ten items and provides a general assessment of perceived usability. It is widely appreciated because of its simplicity, reliability, and ease of administration [60].

System Usability Scale (SUS)						☒
1	I think that I would like to use this system frequently.	1	2	3	4	5
2	I found the system unnecessarily complex.	1	2	3	4	5
3	I thought the system was easy to use.	1	2	3	4	5
4	I think that I would need the support of a technical person to be able to use this system.	1	2	3	4	5
5	I found the various functions in this system were well-integrated.	1	2	3	4	5
6	I thought there was too much inconsistency in this system.	1	2	3	4	5
7	I would imagine that most people would learn to use this system very quickly.	1	2	3	4	5
8	I found the system very cumbersome to use.	1	2	3	4	5
9	I felt very confident using the system.	1	2	3	4	5
10	I needed to learn a lot of things before I could get going with this system.	1	2	3	4	5

Figure 26: Visual representation of the System Usability Scale - [50]

Although originally developed for conventional interfaces, the SUS has been successfully applied to virtual reality environments. The User Experience Questionnaire (UEQ) represents another widely adopted assessment instrument. Unlike the SUS, it evaluates both pragmatic qualities, such as efficiency and dependability, and hedonic qualities, including stimulation and novelty UEQ. An example of this is illustrated in Figure 27.

	1	2	3	4	5	6	7		
annoying	☐	☐	☐	☐	☐	☐	☐	enjoyable	1
not understandable	☐	☐	☐	☐	☐	☐	☐	understandable	2
creative	☐	☐	☐	☐	☐	☐	☐	dull	3
easy to learn	☐	☐	☐	☐	☐	☐	☐	difficult to learn	4
valuable	☐	☐	☐	☐	☐	☐	☐	inferior	5
boring	☐	☐	☐	☐	☐	☐	☐	exciting	6
not interesting	☐	☐	☐	☐	☐	☐	☐	interesting	7
unpredictable	☐	☐	☐	☐	☐	☐	☐	predictable	8
fast	☐	☐	☐	☐	☐	☐	☐	slow	9
inventive	☐	☐	☐	☐	☐	☐	☐	conventional	10
obstructive	☐	☐	☐	☐	☐	☐	☐	supportive	11
good	☐	☐	☐	☐	☐	☐	☐	bad	12
complicated	☐	☐	☐	☐	☐	☐	☐	easy	13
unlikable	☐	☐	☐	☐	☐	☐	☐	pleasing	14
usual	☐	☐	☐	☐	☐	☐	☐	leading edge	15
unpleasant	☐	☐	☐	☐	☐	☐	☐	pleasant	16
secure	☐	☐	☐	☐	☐	☐	☐	not secure	17
motivating	☐	☐	☐	☐	☐	☐	☐	demotivating	18
meets expectations	☐	☐	☐	☐	☐	☐	☐	does not meet expectations	19
inefficient	☐	☐	☐	☐	☐	☐	☐	efficient	20
clear	☐	☐	☐	☐	☐	☐	☐	confusing	21
impractical	☐	☐	☐	☐	☐	☐	☐	practical	22
organized	☐	☐	☐	☐	☐	☐	☐	cluttered	23
attractive	☐	☐	☐	☐	☐	☐	☐	unattractive	24
friendly	☐	☐	☐	☐	☐	☐	☐	unfriendly	25
conservative	☐	☐	☐	☐	☐	☐	☐	innovative	26

Figure 27: Visual representation of the User Experience Questionnaire - UEQ

An interesting alternative is the Game Experience Questionnaire (GEQ), which investigates experiential dimensions such as immersion, flow, competence and affective engagement [61]. These constructs provide a deeper understanding of the emotional aspects associated with interaction in virtual environments. Figure 28 provide an example of GEQ.

	1	2	3	4	5
	No		Sort of		Yes
1. I lose track of time	3	0	3	2	9
2. Things seem to happen automatically	1	0	3	4	9
3. I feel different	2	1	3	3	8
4. I forget where I am	6	1	2	2	6
5. Things don't seem real	7	0	2	5	3
6. I feel spaced out or goofy	4	4	2	1	6
7. Time seems to kind of stand still or stop	6	0	3	4	4
8. It seems like something outside of me makes me move	4	1	4	2	6
9. I play without thinking about it	3	2	4	2	6
10. Things seem to be in slow motion	8	0	3	1	5

Notes. Numbers in bold indicate number of children who chose that response, total number of children = 17.

Figure 28: Visual representation of the Game Experience Questionnaire - [61]

3.6 Indicator-Based Comparison and Suitability for the Proposed Experiment

The assessment tools that have been presented in the previous sections are typically organized in specific dimensions or macro-areas, each of which related to a certain psychological, cognitive or experience-related construct. While the questionnaires vary in their format and objectives, there are eight indicators that were found to be relevant for a consistent evaluation of the instruments in question: Emotional Valence, Emotional Arousal, Stress and Anxiety, Cognitive Workload, Situational Awareness, Presence and Immersion, Agency, Perceived Control, Usability and Interaction Quality. Evaluating the significance of each indicator allows for the identification of questionnaires containing the most crucial dimensions, providing a foundation for the future development of a questionnaire grounded in these selected metrics. The assessment of the coverage of these eight indicators by each questionnaire was done on a five-point scale. Specifically, if the number 1 was assigned to an indicator, it means that the construct is not represented in the questionnaire. Number 2 stands for poor or indirect coverage; 3 for partial coverage; 4 for strong coverage and 5 for direct assessment of the corresponding construct in the instrument.

Table 3: Questionnaire coverage of emotional and cognitive indicators. Scores range from 1 (not meaningfully assessed) to 5 (direct and explicit assessment).

Questionnaire	Emotional Valence	Emotional Arousal	Stress & Anxiety	Cognitive Workload
Self-Assessment Manikin (SAM)	5	5	2	1
Visual Analogue Scale (VAS)	4	4	5	3
State-Trait Anxiety Inventory (STAI)	2	3	5	2
NASA Task Load Index (NASA-TLX)	1	2	3	5
Situation Awareness Rating Technique (SART)	1	4	3	4
Presence Questionnaire (PQ)	1	2	1	2
Multimodal Presence Scale (MPS)	2	2	1	1
System Usability Scale (SUS)	1	1	1	2
User Experience Questionnaire (UEQ)	3	3	1	2

Table 4: Questionnaire coverage of situational, immersive and interaction-related indicators. Scores range from 1 (not meaningfully assessed) to 5 (direct and explicit assessment).

Questionnaire	Situational Awareness	Presence & Immersion	Agency & Perceived Control	Usability & Interaction Quality
Self-Assessment Manikin (SAM)	1	1	4	1
Visual Analogue Scale (VAS)	2	2	3	2
State-Trait Anxiety Inventory (STAI)	1	1	2	1
NASA Task Load Index (NASA-TLX)	3	1	3	2
Situation Awareness Rating Technique (SART)	5	2	3	1
Presence Questionnaire (PQ)	3	5	4	4
Multimodal Presence Scale (MPS)	2	5	4	1
System Usability Scale (SUS)	1	1	3	5
User Experience Questionnaire (UEQ)	1	2	4	5

Subsequently, the relevance of the eight indicators is assessed in Table 5 based on their utility for evaluating the present experiment. This approach enables the identification of the most suitable question sets for constructing the future questionnaire. The evaluation is consistently

performed on a scale ranging from 1 to 5 where 1 means low relevance and 5 means very high relevance.

Table 5: Relevance of the selected emotional, cognitive, immersive and interaction-related indicators to the Proposed CAVE experiment

Experiment	Emotional Valence	Emotional Arousal	Stress & Anxiety	Cognitive Workload	Situational Awareness	Presence & Immersion	Agency & Perceived Control	Usability & Interaction Quality
Politecnico di Torino Experimental Profile	4	5	5	5	5	4	5	3

The questionnaire coverage profiles and their experimental validity are represented through overlapping radar charts. For each instrument, the blue profile identifies the indicators primarily addressed by the questionnaire, while the orange one represents the dimensions considered most relevant to the experimental scenario. The degree of overlap between the two profiles provides a visual indication of the correspondence between the measurement scope of each questionnaire and the requirements of the CAVE experiment.

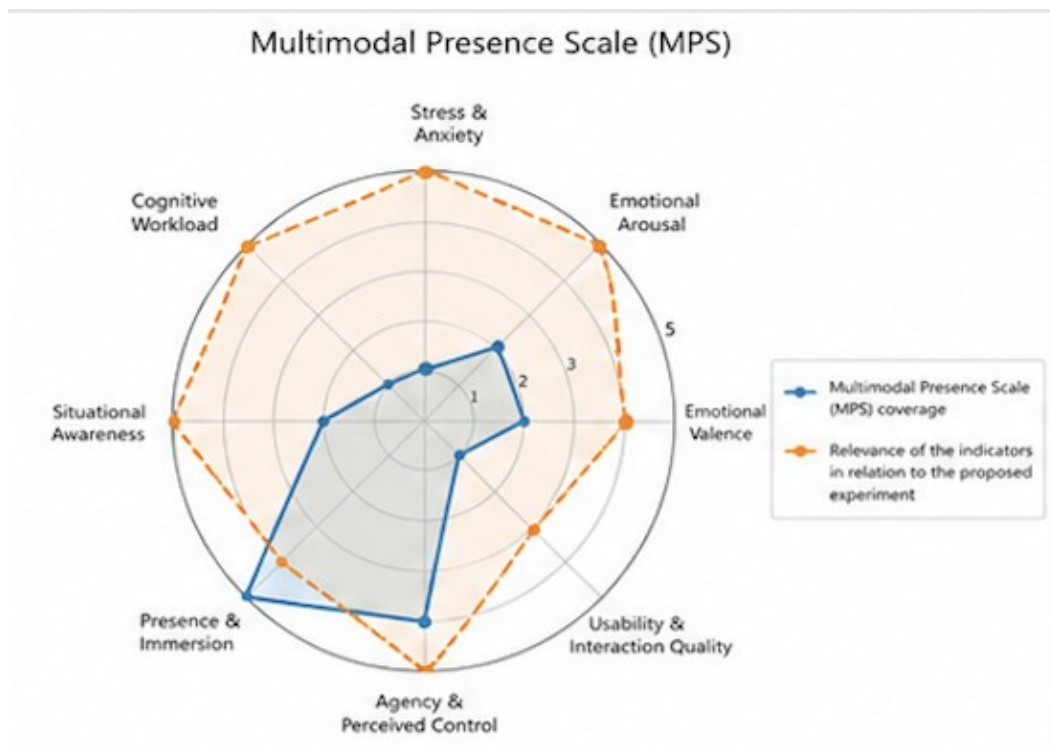


Figure 29: Radar chart illustrating the relevance of the Multimodal Presence Scale (MPS) dimensions to the proposed experiment

The MPS presents its strongest alignment with Presence and Immersion, with questionnaire coverage closely corresponding to the high relevance of this dimension within the CAVE experiment. Agency and Perceived Control also shows good proximity to the experimental profile. The remaining indicators present considerable differences between questionnaire coverage and experimental relevance. The MPS profile is therefore primarily aligned with the need to assess the perceived immersive quality of the proposed experiment scenario.

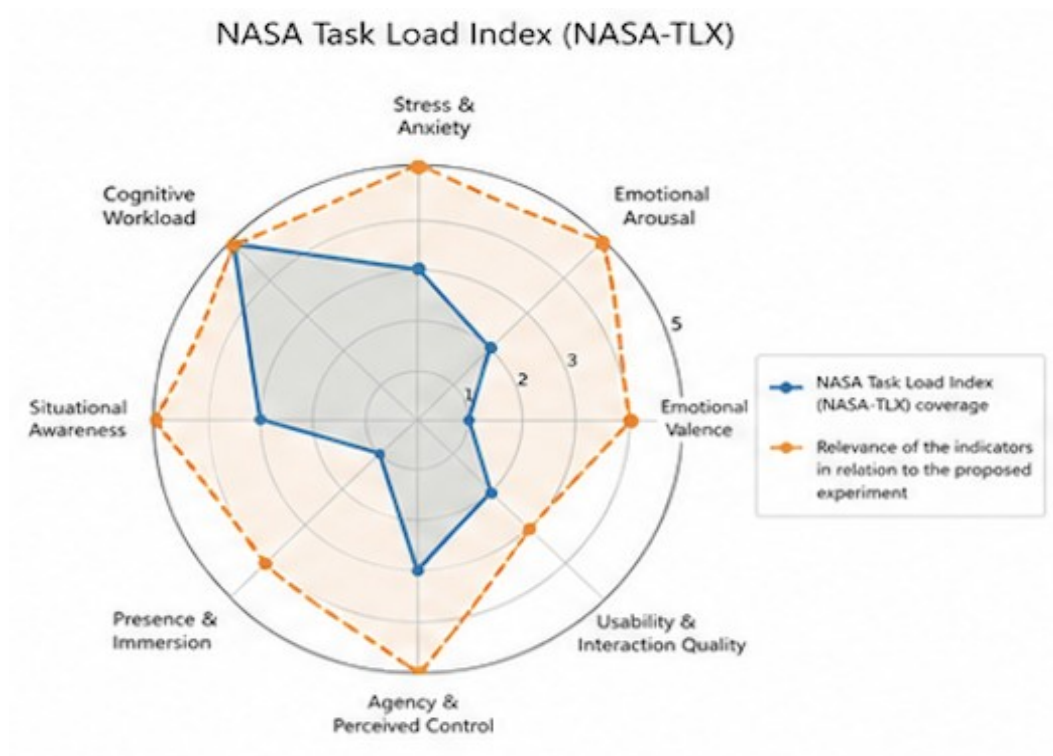


Figure 30: Radar chart illustrating the relevance of the Nasa Task Load Index (NASA-TLX) dimensions to the proposed experiment

The NASA-TLX shows a perfect correspondence for Cognitive Workload, one of the central requirements of the proposed experimental scenario. Partial proximity is also observed for Stress and Anxiety, Situational Awareness, and Agency and Perceived Control. These dimensions are indirectly connected with the cognitive effort required during the sequence of tasks and emergency management. The radar profile therefore identifies Cognitive Workload as the principal point of correspondence between NASA-TLX and the experimental requirements.

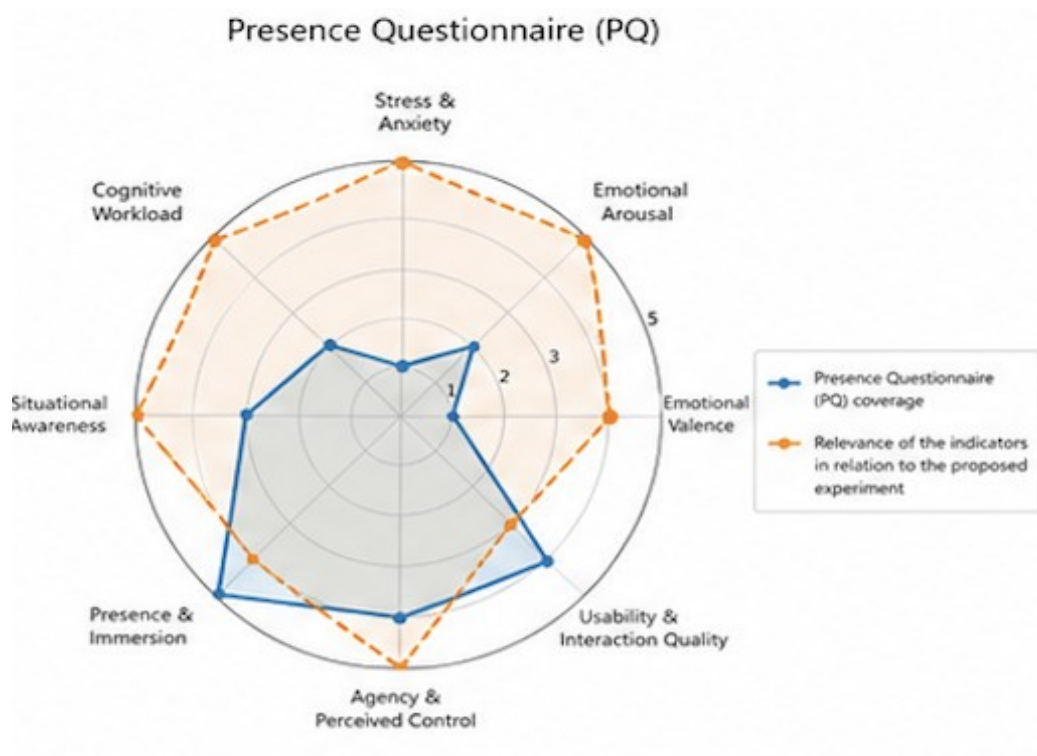


Figure 31: Radar chart illustrating the relevance of the Presence Questionnaire (PQ) dimensions to the proposed experiment

The strongest correspondence of the PQ is observed for Presence and Immersion, where questionnaire coverage is even slightly higher than the relevance attributed to the experimental scenario. Agency and Perceived Control also shows a close correspondence between the two profiles. A moderate proximity can be observed for Situational Awareness and Usability and Interaction Quality. The resulting radar profile identifies the PQ as particularly aligned with the immersive and interaction-related requirements of the proposed experiment.

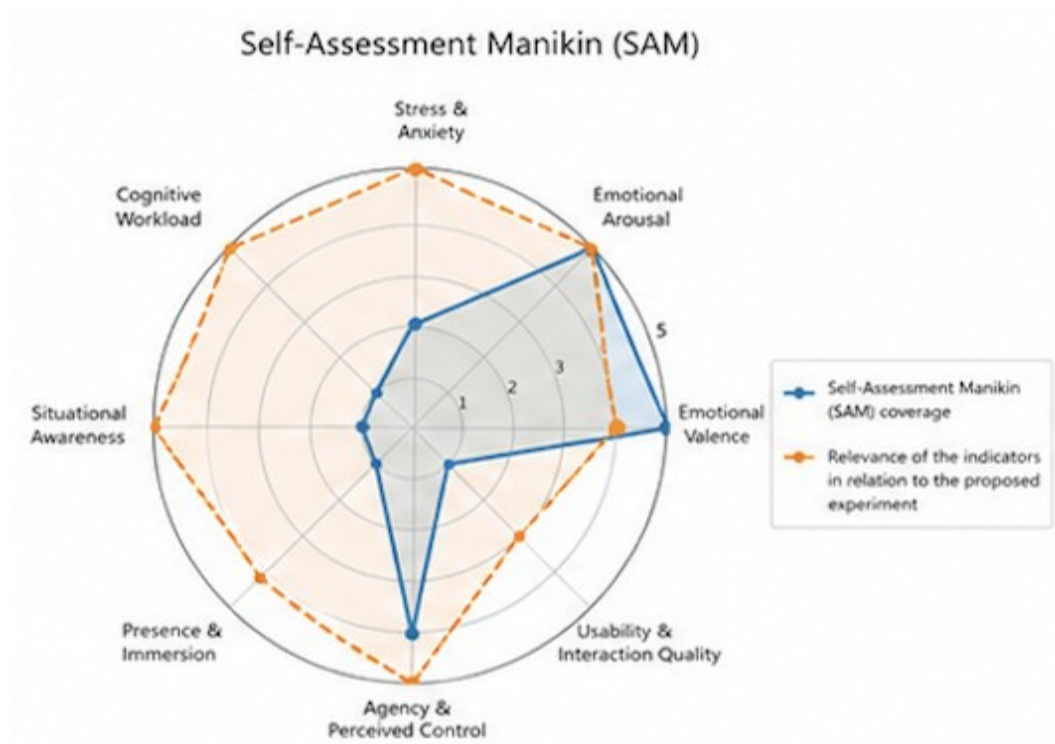


Figure 32: Radar chart illustrating the relevance of the Self-Assessment Manikin (SAM) dimensions to the proposed experiment

The SAM profile shows a perfect correspondence with the experimental requirements for Emotional Arousal, while Emotional Valence is also closely aligned with the relevance attributed to the proposed experiment scenario. A relatively strong correspondence can also be observed for Agency and Perceived Control, reflecting the relevance of perceived dominance and control during active interaction with the emergency scenario. The remaining indicators show a substantial distance from the experimental profile, particularly Cognitive Workload and Situational Awareness.

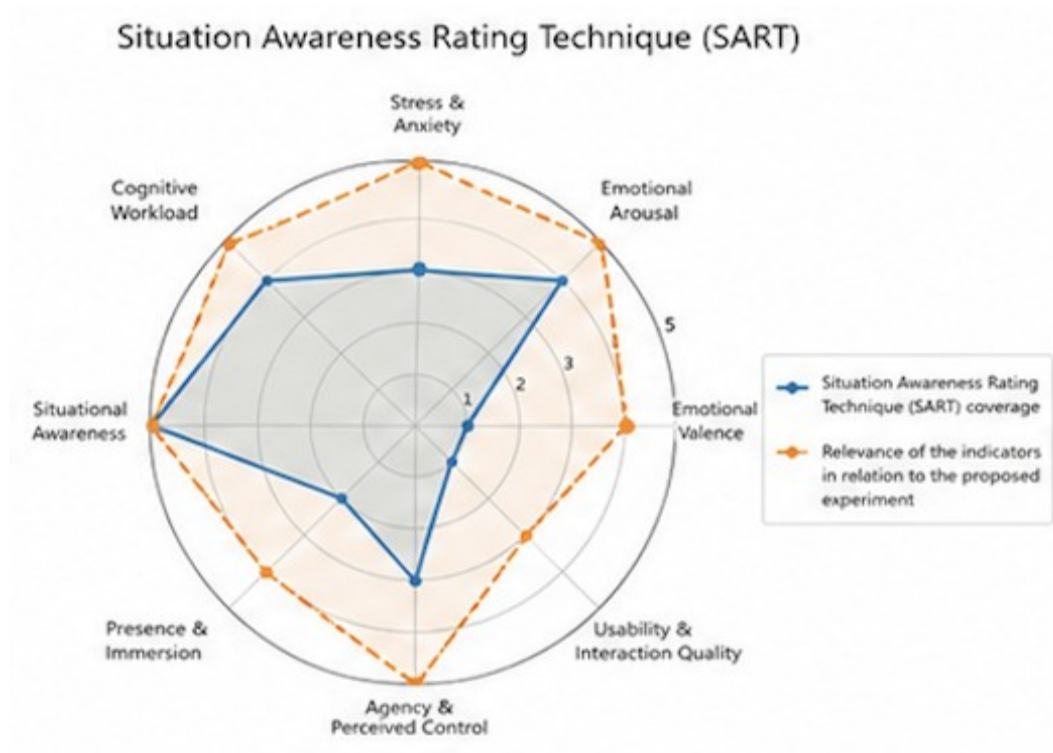


Figure 33: Radar chart illustrating the relevance of the Situation Awareness Rating Technique (SART) dimensions to the proposed experiment

The SART profile presents a perfect correspondence with the experimental relevance assigned to Situational Awareness, making this dimension its principal point of alignment with the proposed experiment scenario. Strong proximity is also observed for Emotional Arousal and Cognitive Workload, where questionnaire coverage approaches the experimental requirements. Agency and Perceived Control shows a weaker correspondence. In contrast, the instrument is poorly aligned with Presence and Immersion and shows no meaningful correspondence with Emotional Valence or Usability and Interaction Quality.

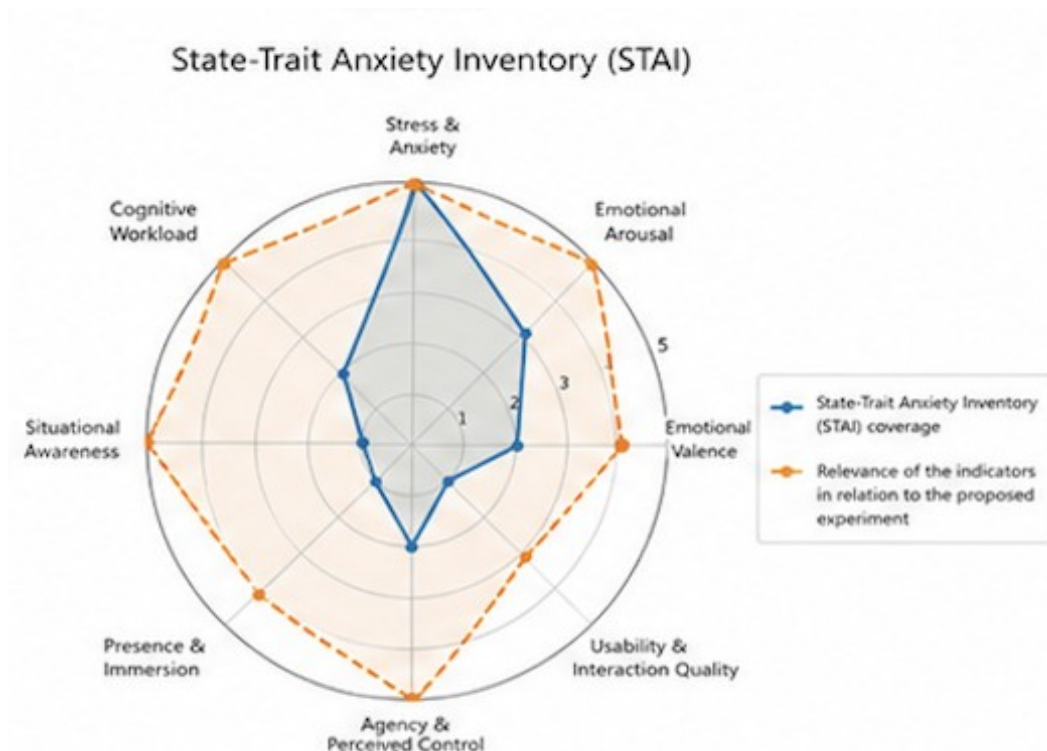


Figure 34: Radar chart illustrating the relevance of the State-Trait Anxiety Inventory (STAI) dimensions to the proposed experiment

The strongest correspondence is observed for Stress and Anxiety, where questionnaire coverage perfectly matches experimental relevance. Emotional Arousal shows a moderate proximity to the experimental profile, supporting the analysis of emotional activation associated with anxiety. However, the substantial distance observed across the other indicators reflects the highly focused nature of the STAI profile. Its relevance to the proposed experiment is therefore concentrated primarily on the anxiety response generated by the emergency event.

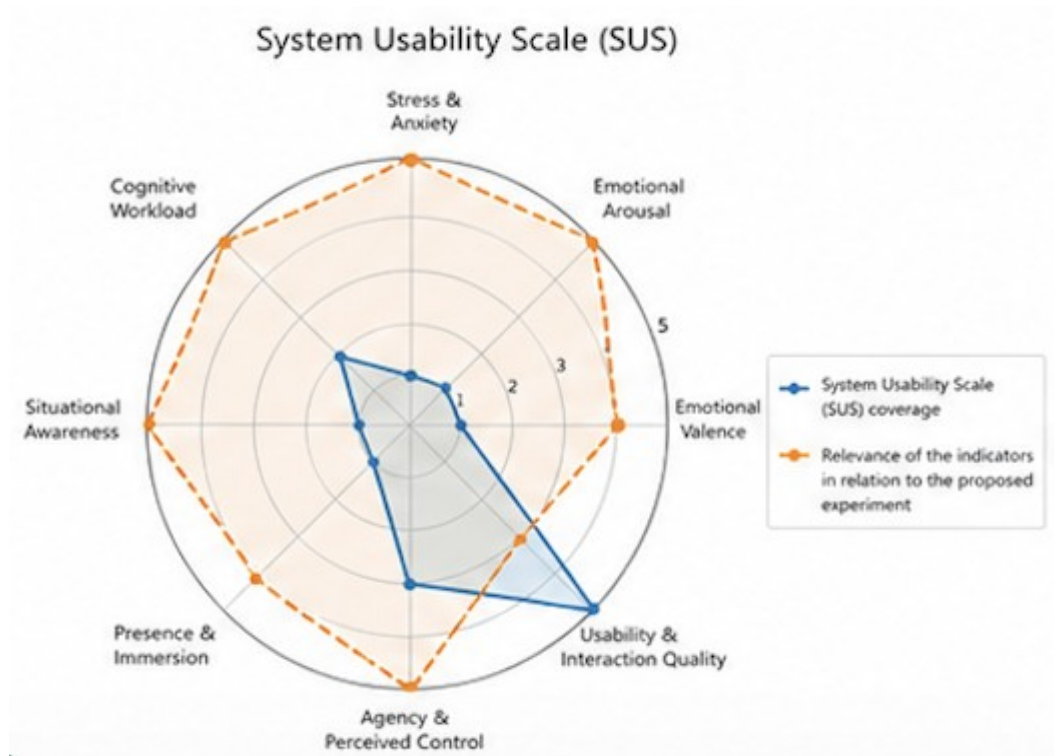


Figure 35: Radar chart illustrating the relevance of the System Usability Scale (SUS) dimensions to the proposed experiment

The SUS profile shows its principal correspondence with Usability and Interaction Quality. Questionnaire coverage is higher than the experimental relevance assigned to this indicator, but the dimension remains relevant because the participant must interact effectively with the virtual environment. A moderate proximity can also be observed for Agency and Perceived Control. The remaining dimensions show substantial distance from the experimental profile, confirming that the principal point of correspondence concerns the quality and clarity of system interaction.

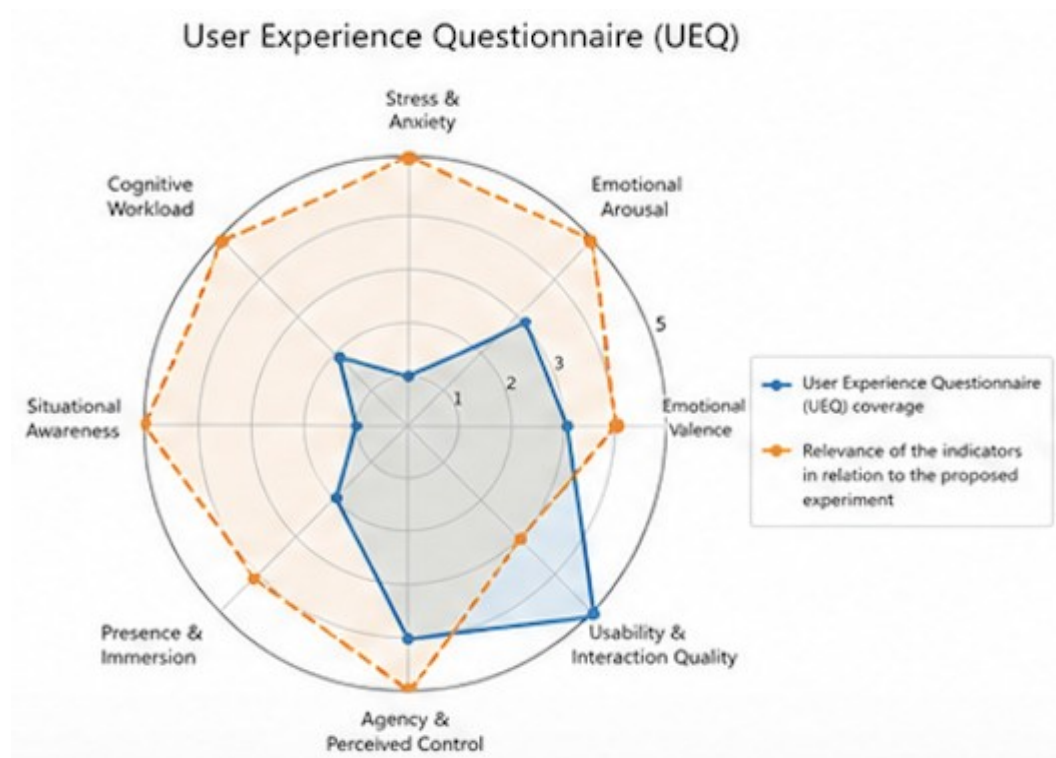


Figure 36: Radar chart illustrating the relevance of the User Experience Questionnaire (UEQ) dimensions to the proposed experiment

The UEQ shows a strong correspondence with Agency and Perceived Control, where questionnaire coverage closely approaches the experimental relevance profile. Usability and Interaction Quality also represents an important point of alignment, although its questionnaire coverage exceeds the relevance assigned to this dimension in the experimental scenario. Emotional Valence and Emotional Arousal show moderate proximity to the experimental requirements. The UEQ profile therefore presents a broader correspondence with interaction-related and experiential aspects of the proposed experiment.

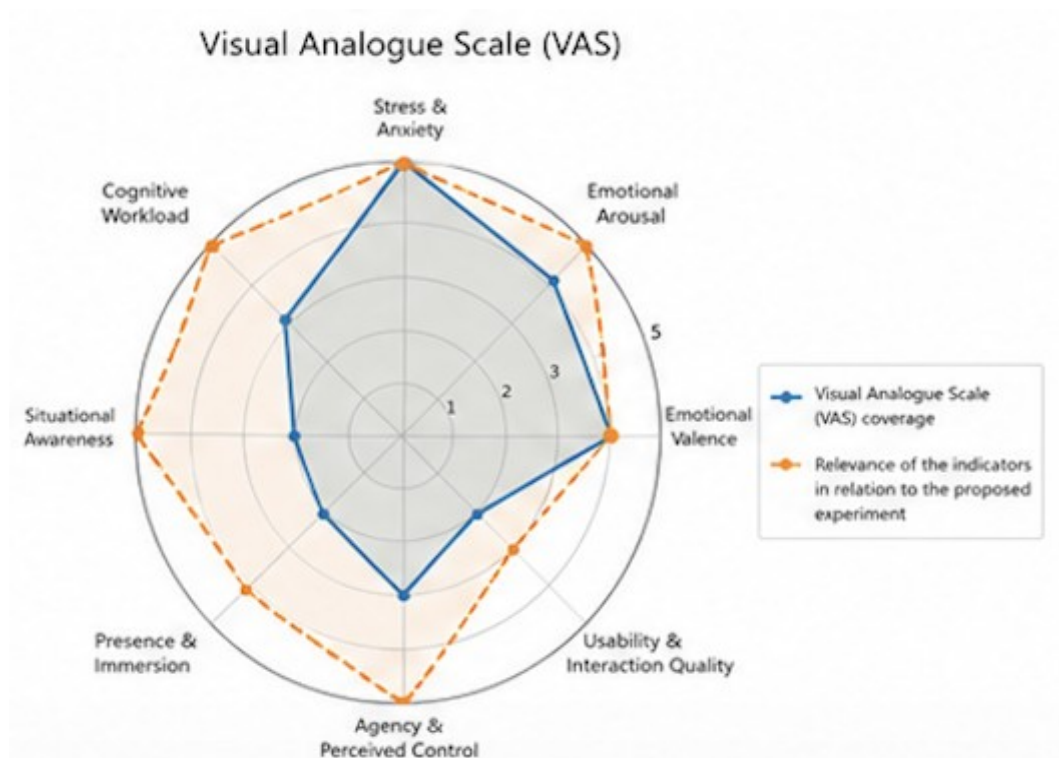


Figure 37: Radar chart illustrating the relevance of the Visual Analogue Scale (VAS) dimensions to the proposed experiment

The VAS presents one of the closest correspondences with the emotional profile required by the experiment. Stress and Anxiety perfectly match the experimental relevance profile, while Emotional Valence and Emotional Arousal remain very close to the required values. Cognitive Workload and Agency and Perceived Control show a moderate correspondence, although their coverage remains lower than the relevance assigned to these dimensions in the experimental scenario. The resulting profile confirms the strong relevance of VAS-based measures for the principal emotional components of the experiment.

4. The Evolution of Virtual Reality: Technological Milestones and Cost Dynamics

4.1 Historical timeline of VR technologies and differences between their technological characteristics

The development of virtual reality technologies can be interpreted as a gradual convergence of innovations in hardware, software, visualization techniques and interaction models. Figure 38 summarizes the historical evolution of the principal virtual reality paradigms, highlighting the major milestones that shaped the development of Desktop VR, Head-Mounted Displays (HMDs) and CAVE systems from the 1950s to the present day. The historical progression of immersive technologies did not follow a strictly linear path; instead, it evolved through parallel advances. Although they represent distinct technological trajectories, their paths are simultaneously interconnected evolving from experimental prototypes into scalable and consumer-oriented immersive solutions [62], [63]. Between the earliest milestones in the history of immersive simulation, the Sensorama, created by Morton Heilig during the 1950s and formally described in 1962, represented a pioneering attempt to reproduce multisensory experiences through stereoscopic images, sound, vibration, airflow, and olfactory stimuli [64]. It anticipated several concepts that would later become central to immersive virtual reality systems. In 1968 with Ivan Sutherland's head-mounted display, widely known as the "Sword of Damocles" [65], a technological development point occurred; this apparatus represented the first attempt to combine computer-generated graphics with real-time perspective adaptation based on head movements. Despite its limited graphical performance and cumbersome mechanical structure, the system established the conceptual foundations of contemporary HMD technologies and interactive immersive visualization [66]. Throughout the 1980s, immersive technologies began attracting growing scientific and commercial attention particularly through the development of systems that combined virtual visual environments with hand-based interaction, allowing users to perform actions and manipulate elements within virtual spaces [67]. The 1990s represented a decisive stage in the evolution of the principal VR paradigms. HMD technologies improved substantially in terms of resolution, tracking accuracy, and ergonomic design, while Desktop VR systems became increasingly accessible due to the rapid spread of personal computers and three-dimensional graphics accelerators. During the same period, a particularly influential innovation emerged with the

introduction of the CAVE (Cave Automatic Virtual Environment) at the University of Illinois at Chicago in 1992, allowing collaborative visualization, scientific simulation, engineering applications and research activities [68]. During the 2000s, advances in graphics processing units (GPUs), rendering algorithms and simulation software considerably contributed to the expansion of the capabilities of immersive systems. Desktop VR platforms benefited from the evolution of three-dimensional graphics technologies such as **OpenGL** and DirectX [69], [70], enabling increasingly realistic and interactive environments at lower implementation costs. A further major transformation emerged during the 2010s with the appearance of modern consumer-oriented HMDs; during this period, more affordable innovations, such as Google Cardboard, drove the widespread adoption of HMDs, thereby fostering their democratization. The Oculus Rift prototype, introduced in 2012, initiated a new generation of immersive technologies characterized by enhanced display quality, reduced latency and lower implementation expenses. Shortly afterward, devices such as the HTC Vive introduced room-scale tracking systems, enabling users to physically navigate virtual environments. The rapid diffusion of game engines and development frameworks further accelerated the creation of immersive applications by reducing technical barriers for developers [71]. The commercialization of standalone HMDs constituted another significant milestone in the democratization of virtual reality technologies because of the integrated displays, processing units and tracking technologies directly within the headset. This transition substantially improved portability, accessibility and scalability, contributing to the extensive diffusion of immersive technologies across gaming, education, healthcare, remote collaboration, and professional training [72]–[75]. More recently, the 2020s introduced new paradigms centered on mixed reality and spatial computing. The most recent milestones reported in Figure 38 highlight the transition toward mixed reality, standalone immersive devices and increasingly integrated spatial computing ecosystems [76]–[79].

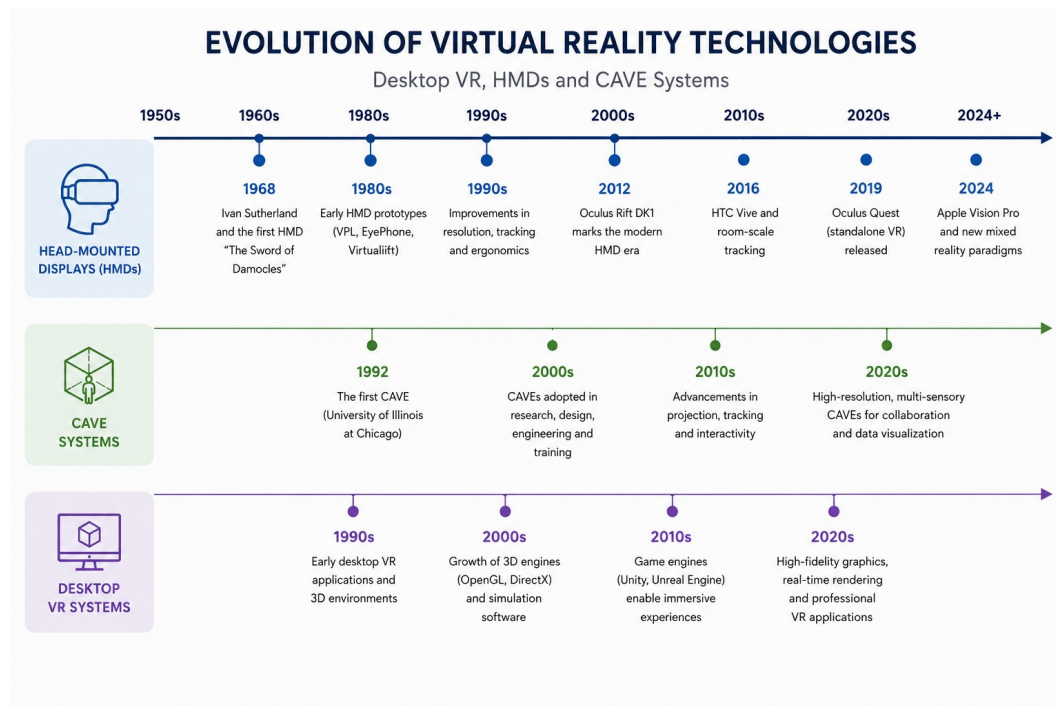


Figure 38: Evolution of Virtual Reality Technologies across Desktop VR, CAVE systems, and Head-Mounted Displays - [64]-[79].

4.2 Cost Evolution and Economic Accessibility

4.2.1 Cost Structure of VR Technologies

The economic characteristics of virtual reality technologies differ substantially according to the system architecture, hardware requirements, and infrastructural complexity involved. The following sections therefore examine Desktop VR, HMD, and CAVE cost dynamics individually. For each system, the analysis considers the principal hardware, software, infrastructural and maintenance cost components together with scalability.

4.3 Detailed Cost Analysis of VR Technologies

This section presents a detailed cost analysis of Desktop VR, Head-Mounted Displays (HMDs), and CAVE systems.

4.3.1 Desktop VR technology cost analysis and evolution

Desktop-based virtual reality represents one of the most economically accessible forms of immersive technology. The hardware requirements are generally limited to a conventional desktop computer, a monitor and standard input devices, such as a keyboard, mouse or game controller [80]. The main cost components, infrastructural requirements and estimated implementation costs associated with Desktop VR systems are summarized in Table 6. More advanced configurations may also include dedicated graphics processing units (GPUs), particularly when real-time rendering of complex three-dimensional environments and interactive simulations is required. Unlike fully immersive systems, Desktop VR primarily relies on widely available consumer hardware. This considerably reduces implementation costs and makes the technology easier to adopt in educational, industrial and research settings [81]. As shown in Table 6, a current professional desktop workstation, comprising a central processing unit (CPU), a dedicated graphics processing unit (GPU), system memory and storage, typically ranges in price from USD 1,300 to USD 1,700 [82], [83]. This estimate is based on configurations officially recommended by manufacturers such as HP for simulation and virtual reality (VR) applications. Alternatively, entry-level professional workstations can be acquired for approximately USD 1,000, as evidenced by the Dell Precision series. Regarding the peripherals recommended for VR simulations, high-end setups, such as a Dell Ultrasharp 27 monitor paired with a professional keyboard and mouse, total approximately USD 570 [84]. However, by adopting more affordable display options, the overall estimated cost for peripherals can be reduced to a range between USD 150 and USD 500. In terms of development platforms, Unity is identified as the most widely adopted engine, a trend supported by the literature. Nonetheless, various studies also highlight Unreal Engine and other specialized simulation software as prevalent alternatives [85], [86]. Official licensing models indicate that Unity frequently offers free access to research institutions, students, and small-scale developers, whereas the Unity Pro license is priced at approximately USD 210 per month. Similarly, Unreal Engine provides free tiers for academic use, while its commercial license costs roughly USD 1,850 annually. Consequently, software expenditures can fluctuate between USD 0 and

approximately USD 2,000 per year, depending on the required licensing tier [86]. The infrastructural requirements of Desktop VR are also relatively limited. These systems can be installed in conventional offices, classrooms, laboratories, or even domestic environments, without the need for dedicated tracking technologies or specialized immersive facilities. As a result, implementation costs are mainly linked to computing hardware and software acquisition rather than to physical infrastructure. Finally, regarding operational and maintenance costs, these parameters are rarely explicitly detailed in the existing literature. However, an annual estimate of USD 100 to USD 300 can be established. This projection is derived from standard workstation lifecycle management metrics, which typically allocate 5% to 10% of the initial hardware investment to ongoing maintenance.

Table 6: Representative cost components and implementation requirements associated with Desktop VR system derived from the technological characteristics, deployment configurations, and hardware requirements reported in the literature[68, 83–87, 98]

Cost Component	Description	Approximate Cost
Hardware	Desktop PC, monitor, keyboard/mouse, optional dedicated GPU and CPU	\$1,300-\$2000
Software	Development platforms (Unity, Unreal Engine), CAD and simulation software	\$0-\$2,000+
Maintenance	Hardware upgrades, software updates, and peripheral replacement	\$100-\$300
Scalability	Easily replicable across multiple users and workstations	Very High
Approximate Total Cost	Complete Desktop VR workstation	\$1,400-\$4000

Drawing upon the literature, it is possible to estimate the historical average cost of a Desktop VR setup in order to trace its pricing trend over time. Based on the historical evolution of professional graphics workstations reported in the literature, the average cost of the workstation component can be estimated at approximately USD 20,000 during the 1990s peripheral devices (monitor, keyboard, and mouse) accounted for roughly \$2,150, and software licenses required a minimum investment of \$2,000. Furthermore, maintenance costs were significantly higher due to the lower reliability and performance of the hardware at the time. Consequently, the total average cost amounted to approximately \$25,000. In the 2000s, technological advancements in CPU and GPU architectures led to a substantial reduction in workstation prices, which fell to approximately \$7,000. The cost of peripheral devices dropped to about \$800, software expenses decreased to a minimum of \$1,000, and maintenance costs were estimated at \$1,200, resulting in a total expenditure of approximately \$10,000. By 2010, the cost of workstations had halved, a trend similarly observed in the prices of monitors and input devices. Average software costs were estimated at approximately \$500, while maintenance expenses stabilized around \$700, yielding a final estimated total of \$5,500 [80], [82], [83].

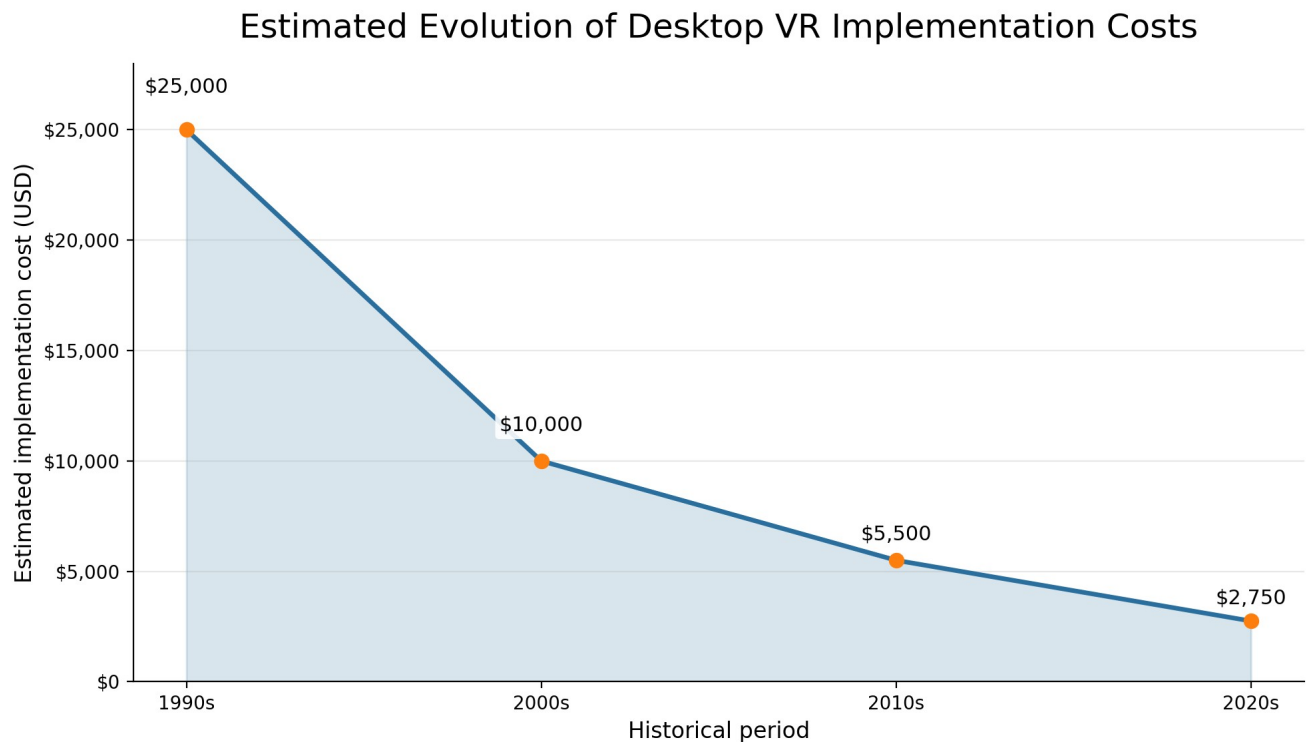


Figure 39: Estimated Evolution of Desktop VR Implementation Costs from the 1990s to the 2020s - [80], [82], [83]

4.3.2 HMD VR Technology

Head-Mounted Display (HMD) systems present a more complex economic structure than Desktop VR, while remaining considerably more accessible than large-scale immersive infrastructures such as CAVE environments. Their implementation costs are primarily influenced by the adopted device architecture, the computing hardware required to support immersive applications, and the software ecosystem on which the overall experience relies. To accurately estimate the total cost of ownership for Head-Mounted Displays (HMDs), the overall investment must be categorized into distinct components: the headset, controllers and tracking systems, a VR-Ready PC and software licenses [87]. Furthermore, ongoing maintenance costs must be factored into the analysis. Based on official manufacturer retail pricing, the headset itself is typically priced at approximately USD 499, as demonstrated by devices such as the Meta Quest 3 and the standalone Valve Index headset [88], [89]. Input peripherals and tracking mechanisms incur additional expenses; for instance, the Valve Index

controllers and two external base stations amount to approximately USD 279 and USD 149, respectively. During the 2020s, technological advancements led to the development and subsequent market launch of standalone VR devices. These headsets operate as fully independent systems, integrating essential built-in components such as memory, a mobile processor, and a battery [89]–[91]. However, despite the inclusion of a mobile processor, their computational power remains significantly limited when compared to the dedicated Graphical Processing Units (GPUs) of traditional workstations. Consequently, executing complex simulations natively on standalone headsets is generally unfeasible, necessitating tethered or wireless cooperation with a dedicated computer. Nevertheless, the proliferation of standalone technology has drastically reduced the baseline cost of VR headsets, lowering the entry price to as little as \$299 [92]. The computational foundation, a VR-Ready PC equipped with a capable CPU and a dedicated GPU, aligns with the pricing parameters previously established in the desktop VR analysis, generally falling within the USD 1,000 to USD 1,500 range [93]. A similar paradigm applies to software requirements: the most widely adopted development platforms, Unity and Unreal Engine, range from USD 0 to approximately USD 2,000, consistent with prior estimations [85], [86]. Notably, physical infrastructure no longer constitutes a major expenditure in modern setups, primarily due to the widespread integration of inside-out tracking technologies, which negate the need for dedicated tracking spaces or external sensor installations. Finally, maintenance costs for this technology are estimated to fluctuate between USD 100 and USD 500. This projection accounts for the probable replacement of controllers, sensor calibration, auxiliary accessories, and software updates, and is derived directly from the current pricing of Original Equipment Manufacturer (OEM) replacement parts [94].

Table 7: Representative cost structure of PC-based HMD virtual reality systems [87], [88], [94]

Cost Component	Description	Approximate Cost
Headset	Oculus Rift, HTC Vive and Meta Quest 2	\$299–\$799
Controllers & Tracking	Motion controllers and external tracking stations	\$150–\$280
VR-Ready PC	Gaming workstation with dedicated GPU	\$1,000–\$1,500
Software	VR applications, development platforms and professional licenses	\$0–\$2,000+
Maintenance	Controller replacement, sensor calibration and software updates	\$100–\$500
Approximate Total Cost	Complete PC-based immersive setup	\$1,550–\$5,000+

Regarding the cost dynamics of Head-Mounted Displays (HMDs), the historical analysis must commence in the early 2000s, a period when such devices were almost exclusively confined to military and advanced research applications. During this era, HMDs were prohibitively expensive, costing several thousand euros and were characterized by severe technical limitations, including low resolution, restricted fields of view (FOV) and excessive physical weight. A pivotal paradigm shift occurred in 2012, marking the onset of the so-called "Oculus revolution." With the introduction of early development kits (Oculus DK1, DK2) and subsequent consumer releases like the HTC Vive and Oculus Rift CV1, prices plummeted rapidly to a range of USD 599 to USD 799 [95]. This dramatic cost reduction was primarily driven by the expansion of mass production, the integration of LCD and OLED displays repurposed from the

smartphone industry and broader economies of scale. From 2019 to the present, the technology has experienced further significant enhancements, such as increased display resolution and the integration of inside-out and eye-tracking systems, while retail prices have remained remarkably stable. First-generation consumer controllers and tracking systems [96], [97], heavily on external infrared (IR) cameras, lighthouse base stations and complex calibration procedures, which significantly inflated the overall cost. The advent of inside-out tracking revolutionized this architecture by embedding cameras directly into the headset. Consequently, the need for external sensors was eliminated, drastically reducing both maintenance requirements and infrastructural overhead. Because a dedicated, permanently calibrated tracking space is no longer strictly necessary, the hidden infrastructural costs associated with VR deployment have decreased substantially. In terms of the VR-Ready PC, the cost trajectory mirrors the standard performance curve of desktop workstations. Over time, CPUs have become increasingly capable, while GPUs have exponentially enhanced rendering fidelity and overall VR quality. Despite these massive performance leaps, the cost of a capable VR workstation has remained relatively stable, fluctuating between USD 1,000 and USD 2,000. However, the most profound economic transformation has occurred within the software ecosystem. Moreover, the nature of maintenance costs has undergone a complete metamorphosis. Historically, the extensive physical infrastructure and delicate external sensors resulted in high, frequent upkeep expenses. Today, while manual spatial calibration is minimal, new operational costs have emerged, primarily related to hardware consumables (battery replacements, ergonomic facial interfaces, and head straps) and continuous software updates. Consequently, while the annual maintenance budget remains largely stable, estimated between USD 100 and USD 500, the fundamental nature of these operational expenditures (OPEX) has completely shifted from infrastructural upkeep to consumable hardware and software management. The average costs illustrated in the graphs are derived from the study by [80], [94], [98]–[100], which analyzes early research conducted during the 2000s, a period characterized by exceedingly high hardware component prices. Conversely, for the 2010s decade, the primary hardware benchmarks considered are the Oculus DK, Oculus Rift, and HTC Vive.

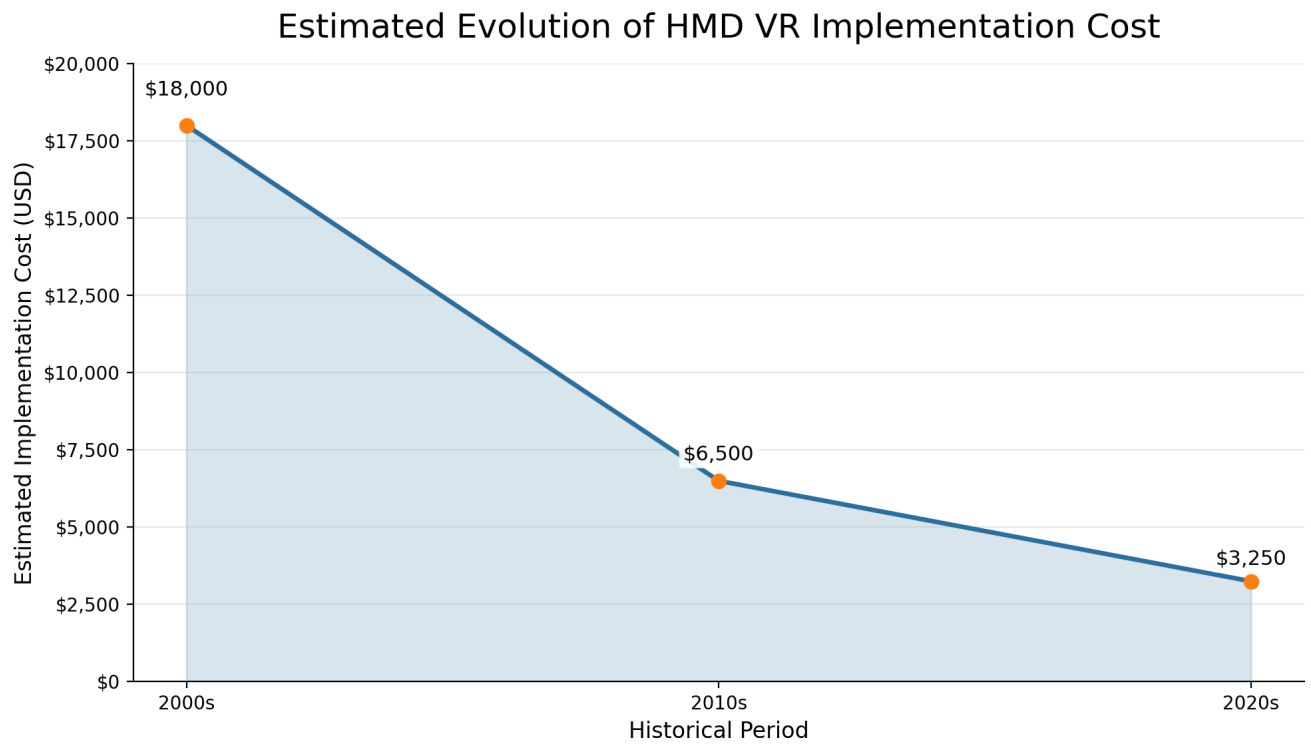


Figure 40: Estimated Evolution of HMD VR Implementation Costs from the 2000s to the 2020s - [80], [94], [98]–[100]

4.3.3 Cost Analysis CAVE

Regarding CAVE (Cave Automatic Virtual Environment) systems, expenditure categories exhibit extreme variability. Depending on the required visual fidelity and hardware quality, the total implementation price can range from USD 50,000 to well over USD 1,000,000. The cost associated with these distinct tiers of CAVE systems is derived from an analysis of several papers that detail the cost structures of systems across varying levels [101]–[111]. To accurately map this broad spectrum, the cost analysis is structured across three distinct tiers: entry-level (low), intermediate (medium) and high-end. The primary capital expenditures are categorized as follows: the projector hardware encompasses the core visual components, including projectors, projection screens, stereoscopic filters, and mirror systems. Based on current market data, costs range from USD 20,000 to USD 40,000 for an entry-level setup, USD 60,000 to USD 120,000 for an intermediate configuration, and USD 150,000 to USD 300,000 for a high-end, state-of-the-art visual system. The rendering hardware costs comprises rendering workstations, dedicated GPUs, hardware synchronization modules, and potentially rendering clusters. Reference data indicates that entry-level computing hardware requires an investment of USD 3,000 to USD 5,000. Intermediate setups necessitate between USD 10,000 and USD 20,000, whereas high-end clustering solutions demand an expenditure of USD 30,000 to USD 80,000. The pricing of tracking hardware is highly contingent upon the desired spatial precision and latency. Consequently, the entry-level tier ranges from USD 8,000 to USD 15,000; the intermediate tier scales from USD 20,000 to USD 50,000; the high-end level needs ultra-precise tracking frameworks that command prices between USD 80,000 and USD 200,000. The audio and network costs include speakers, amplifiers, audio mixers, high-throughput network switches, and synchronization devices. Estimated costs are USD 2,000 to USD 5,000 for the low tier, USD 8,000 to USD 15,000 for the medium tier, and USD 20,000 to USD 40,000 for the high tier. Physical infrastructure represents a massive portion of the overall CAVE budget. This encompasses the construction of rigid projection walls, environmental blackout treatments, specialized HVAC (Heating, Ventilation, and Air Conditioning) systems, complex cabling and professional installation. Categorizing by deployment scale: a small-scale laboratory (entry-level) ranges from USD 20,000 to USD 40,000; a standard university research laboratory (intermediate) requires USD 50,000 to USD 120,000; and a full-scale industrial center (high-

end) necessitates an infrastructural investment of USD 150,000 to USD 500,000. Finally, the software architecture provides two primary financial pathways. Standard development platforms, such as Unity or Unreal Engine, incur minimal costs ranging from USD 0 to USD 2,000. Conversely, deploying specialized, advanced commercial simulation software entails licensing fees that can vary from USD 10,000 to USD 50,000. To accurately assess the maintenance requirements of a CAVE system, it is necessary to evaluate the operational expenditures (OPEX) at the individual component level. For the projection system, annual upkeep is typically estimated at 5% to 10% of the initial projector hardware cost. Maintenance for the tracking system involves relatively low hardware replacement expenses; however, it necessitates highly specialized personnel for continuous calibration and system management. The rendering hardware follows the same maintenance paradigm previously established for desktop VR workstations. Conversely, the physical infrastructure demands the highest maintenance overhead among all virtual reality technologies, generally calculated as an annual recurring cost equivalent to 5% to 10% of the infrastructural capital expenditure (CAPEX). By aggregating these individual operational categories, the total estimated maintenance cost over the system's lifecycle is substantial: ranging from USD 60,000 to USD 180,000 for entry-level configurations, USD 180,000 to USD 500,000 for intermediate setups, and scaling between USD 500,000 and USD 1,200,000 for high-end, industrial-grade systems

Table 8: Representative cost structure of CAVE (Cave Automatic Virtual Environment) systems across different levels of technological complexity - [101]–[111].

Cost Component	Entry-Level CAVE	Mid-Range CAVE	Advanced / High-End CAVE
Projection Hardware Cost	\$20,000–\$40,000	\$60,000–\$120,000	\$150,000–\$300,000+
Rendering Hardware Cost	\$3,000–\$5,000	\$10,000–\$20,000	\$30,000–\$80,000+
Tracking Cost	\$8,000–\$15,000	\$20,000–\$50,000	\$80,000–\$200,000+
Audio & Network Cost	\$2,000–\$5,000	\$8,000–\$15,000	\$20,000–\$40,000+
Infrastructure Cost	\$20,000–\$40,000	\$50,000–\$120,000	\$150,000–\$500,000
Software Cost	\$1,000–\$2,000	\$2,000–\$10,000	\$10,000–\$50,000+
Annual Maintenance Cost	\$5,000–\$10,000	\$15,000–\$30,000	\$40,000–\$80,000+
Approximate Total Cost	\$60,000–\$180,000	\$180,000–\$500,000	\$500,000–\$1,200,000+

Based on the previously analyzed literature and additional studies reflecting the economic trends of this technology over time across all three examined ranges, it is possible to draw conclusions regarding the temporal evolution of implementation costs [112], [113]. Analyzing the historical cost evolution of CAVE systems across the three established tiers (entry-level, intermediate, and high-end) reveals distinct economic trends over four key timeframes: the late 1990s, the mid-2000s, the early 2010s and the present day. Generally, entry-level CAVEs have benefited the most from the democratization of consumer PCs, GPUs and digital projectors, experiencing the steepest proportional price drops. Intermediate systems have also seen significant cost reductions while successfully retaining professional-grade hardware. Conversely, high-end systems have experienced the lowest relative depreciation, as they continue to rely on bespoke, enterprise-grade components to push the boundaries of visual fidelity. The following section details the temporal evolution of these costs

Projector Hardware: For entry-level systems, projection costs plummeted from USD 120,000 in the late 1990s to USD 70,000 (mid-2000s) and USD 40,000 (early 2010s), currently stabilizing between USD 20,000 and USD 40,000. Intermediate systems followed a similar downward curve, dropping from USD 250,000 in the late 1990s to USD 100,000 by the early 2010s, and resting today between USD 60,000 and USD 120,000. High-end projection evolved from a massive USD 500,000 in the late 1990s to a current range of USD 150,000 to USD 300,000.

Rendering Hardware: This category showcases massive depreciation driven by exponential GPU advancements. Entry-level rendering costs fell from USD 80,000 (late 1990s) to a current low of USD 3,000–USD 5,000. Intermediate rendering dropped drastically from USD 250,000 to its current USD 10,000–USD 20,000 range. High-end rendering clusters saw the most substantial absolute reduction, plummeting from USD 600,000 in the late 1990s to currently span between USD 30,000 and USD 80,000.

Tracking Systems: Entry-level tracking decreased steadily from USD 30,000 in the late 1990s to a current estimate of USD 8,000–USD 15,000. Intermediate tracking evolved from USD 80,000 down to USD 20,000–USD 50,000 today. High-end tracking shifted from USD 150,000 in the late 1990s to USD 70,000 by the early 2010s; however, current high-end setups exhibit a wide variance (USD 80,000 to USD 200,000), reflecting the integration of ultra-precise, state-of-the-art optical technologies.

Audio and Network Infrastructure: This segment exhibits the highest historical stability. Entry-level costs marginally decreased from USD 8,000 (late 1990s) to USD 2,000–USD 5,000 today. Intermediate setups shifted from USD 20,000 to USD 8,000–USD 15,000. High-end systems moved from USD 40,000 down to a current stabilization between USD 20,000 and USD 40,000.

Software Licensing: Software represents the most dramatic proportional cost reduction among all variables. Entry-level software dropped from USD 20,000 in the late 1990s to a maximum of USD 2,000 today, heavily driven by accessible game engines. Intermediate software costs fell from USD 60,000 to USD 5,000–USD 15,000. High-end bespoke software licenses decreased from USD 150,000 to a current range of USD 20,000 to USD 50,000.

Physical Infrastructure: Infrastructural costs have also declined, albeit less drastically due to inherent physical construction constraints. Entry-level requirements fell from USD 80,000 (late 1990s) to USD 20,000–USD 40,000 today. Intermediate infrastructure evolved from USD 250,000 down to USD 50,000–USD 120,000. High-end physical setups dropped from USD 500,000 to modern estimates spanning USD 150,000 to USD 500,000.

Maintenance (OPEX): Maintenance expenditures have decreased noticeably across all tiers. Entry-level maintenance dropped from USD 15,000 (late 1990s) to USD 5,000–USD 10,000 today. Intermediate maintenance fell from USD 50,000 to a current range of USD 15,000–USD 30,000. High-end maintenance costs decreased from USD 100,000 down to currently stabilize between USD 40,000 and USD 80,000.

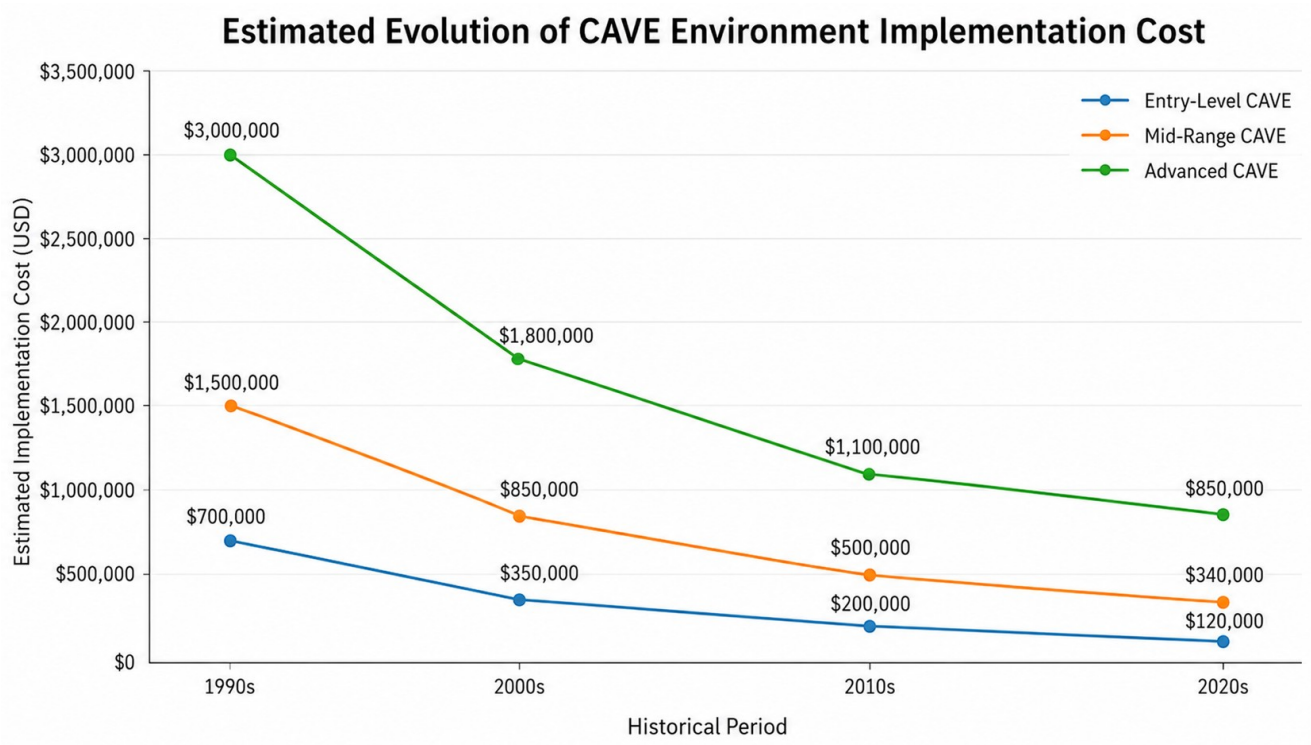


Figure 41: Estimated Evolution of Desktop VR Implementation Costs from the 1990s to the 2020s Across the Three CAVE Categories Analyzed - [112], [113]

4.3 Technological Milestones Driving the Popularity of Head-Mounted Displays

Ultimately, Head-Mounted Displays (HMDs) represent the most successful cost-performance equilibrium across all virtual reality technologies. Their ability to deliver high-fidelity performance, leveraging advanced technological developments, while maintaining accessible price points for the mass market has been the primary catalyst for their widespread adoption. Conversely, the Desktop VR paradigm is fundamentally constrained by its lower levels of immersion, presence, and agency; this critical limitation precludes it from achieving true market dominance. Simultaneously, the prohibitive costs associated with CAVE systems render them entirely unfeasible for the average consumer. Consequently, this technology is destined to thrive exclusively within its optimal ecosystem: specialized research centers and advanced industrial facilities, rather than the consumer-based market. However, the popularity of HMDs has not followed a strictly linear upward trajectory; rather, it has been subject to significant market fluctuations. These oscillations were heavily influenced by the emergence of novel Augmented Reality (AR) and Mixed Reality (MR) technologies. The following section will examine these innovations, which undoubtedly fueled the initial enthusiasm and widespread attention surrounding HMDs. Ultimately, however, this soaring popularity and inflated expectation experienced a stark disconnect with market reality. Failing to achieve the anticipated ubiquitous mainstream adoption, the widespread use of HMDs plateaued, forcing the technology to pivot toward and consolidate within much smaller, specialized market niches rather than the broad consumer segments initially targeted.

4.3.1 Market Factors and the Evolution of HMD Expectations

The fluctuation of HMD popularity and market expectations can be traced through a continuous evolution of technological milestones across Augmented, Virtual, and Mixed Reality. The trajectory began in 2010 when Google introduced Google Glass [114], the first major AR product targeted at the broad consumer market. While it generated massive media attention and pioneered the concept of "wearable computing," the device faced severe criticism regarding privacy concerns and offered limited functionality relative to its high price point of approximately USD 1,500 . This lack of social acceptability ultimately led to its commercial failure in the consumer segment. Shifting strategy in 2014, Google successfully democratized VR with Google Cardboard [115], reducing the barrier to entry to a mere USD 10 to USD 20. By utilizing users' existing smartphones, millions experienced VR for the first time; nevertheless, hardware limitations severely compromised the immersive experience, and the absence of spatial tracking resulted in poor long-term user engagement. Shortly after, in 2015, Microsoft released the HoloLens [116], a device that effectively demonstrated the true potential of MR across the manufacturing, healthcare, and educational sectors, significantly boosting the technology's credibility [117], [118]. However, its prohibitive cost (approximately USD 3,000) and narrow Field of View (FOV) dictated a strategic pivot away from the consumer market, positioning it strictly as a professional tool. The landscape shifted significantly in 2016 with the launch of the Oculus Rift CV1 and HTC Vive [96], [97], marking the dawn of the modern consumer VR era. By introducing "room-scale" tracking and advanced motion controllers, these systems delivered unprecedented levels of immersion and reignited public interest. Conversely, their reliance on expensive, high-performance PCs and cumbersome external tracking infrastructure hindered widespread, mass-market scalability. Attempting to bridge the gap in MR, the Magic Leap One was launched in 2018 [119]. Backed by substantial investments and intense media coverage, it fueled massive expectations for spatial computing, yet ultimately failed

to meet them due to its high retail cost, restricted FOV, and a distinct lack of innovative "killer apps". Building upon previous enterprise successes, Microsoft introduced the HoloLens 2 in 2019 [120], bringing crucial improvements in hand tracking, ergonomics, and overall usability. While this iteration successfully consolidated MR's role in industrial and enterprise environments, its elevated price ensured it remained a niche device strictly confined to the business-to-business (B2B) sector [121]–[123]. A major breakthrough in consumer adoption occurred in 2020 with the release of the Meta Quest 2 [124]. This standalone device rapidly accelerated VR diffusion by offering an accessible price point of approximately USD 300 and eliminating the need for external sensors via inside-out tracking. Despite achieving unprecedented market penetration, continuous daily usage remained limited for many consumers due to ongoing issues with cybersickness, ergonomic discomfort, and a lack of daily utility. Most recently, in 2023, Apple reignited global interest in immersive technologies with the Apple Vision Pro [125], introducing the paradigm of "Spatial Computing" featuring ultra-high-resolution displays, precise eye tracking, and advanced MR capabilities. However, its exorbitant cost of approximately USD 3,500 proved entirely prohibitive for the consumer-based market. Coupled with a nascent software ecosystem, the Vision Pro's market penetration stalled, relegating it exclusively to an ultra-premium tier and demonstrating, once again, the persistent challenge of capturing the mass market.

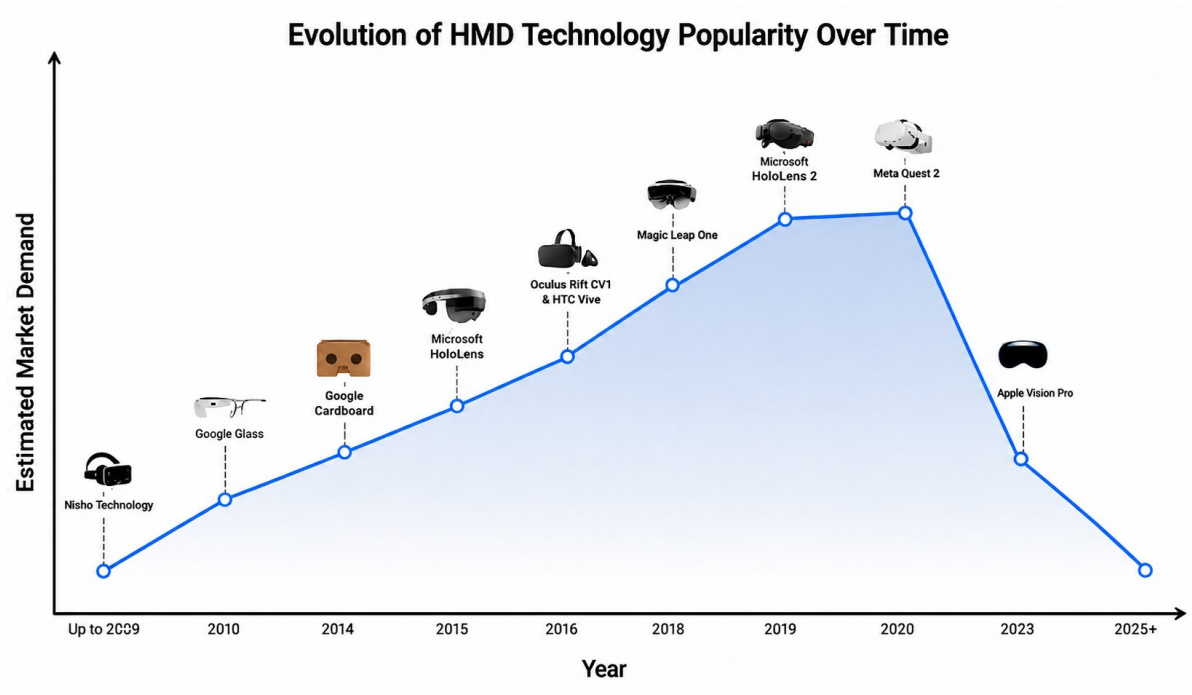


Figure 42: Evolution of HMD Technology Popularity from 2009 to 2025 - [88], [96], [114]-[124], [126]-[128]

5. CAVE Systems for Emotional Research

5.1 The CAVE position in the Current VR Ecosystem

Despite their limited diffusion compared with consumer-oriented immersive technologies, CAVE systems continue to occupy a distinctive position within the current virtual reality landscape. Their adoption remains concentrated in application domains where collaborative interaction, high-quality visualization and controlled immersive environments are essential. As a result, CAVE installations are primarily found in universities, research laboratories, engineering centers and industrial organizations, where they support activities such as scientific visualization, engineering design, digital prototyping, manufacturing, architecture, medical simulation and professional training. Despite these advantages, CAVE systems currently represent a relatively small segment of the immersive technology landscape. Their adoption is generally limited to organizations capable of supporting the substantial investment required for installation, maintenance, and technical management. Dedicated physical spaces, specialized infrastructure and highly customized system integration continue to restrict large-scale deployment, making CAVE environments considerably less widespread than HMD-based solutions. Consequently, rather than competing directly with consumer immersive technologies, CAVE systems have consolidated their role within specialized research and industrial settings where their unique capabilities justify the associated economic and operational requirements.

5.1 Why CAVE is Suitable for Emotional Studies

In the scientific community, the CAVE plays a highly important role. The ability to control an experiment as it unfolds, altering experimental conditions as visual stimuli, spatial configuration, stressful events, soundscapes, interaction dynamics as

demonstrated through the development of the experimental case study, is a game changer for the study of emotions. It is possible to characterize the same experiment with different level of task and stress situation. Combining these characteristics with the possibility of present situation where decision making is required, allows the CAVE to be incredibly useful for the study of human behavior, creating an immersive experience that more closely resembles. In addition, researchers can observe participants during the execution of the experiment; this bolsters the ecological validity of the experiment and facilitates a deeper understanding of the experimental process while researchers observe the participants, making the CAVE very precious for research. CAVE system also enables participants to maintain natural body movements by providing ample spatial freedom, unencumbered by bulky hardware. Furthermore, the capacity to facilitate group experiments, wherein multiple users are immersed simultaneously, makes this apparatus an exceptionally powerful and valuable research tool. It is well established that emotion research relies heavily on interpersonal interactions, whether with physical or virtual agents [129].

5.3 Current Limitations

Despite the advantages discussed in the previous sections, CAVE technology still presents several challenges that limit its widespread adoption and influence its use across different application domains. The most significant constraints are related to implementation costs, infrastructural complexity, maintenance requirements and scalability. From an economic perspective, the high initial investment required to establish a CAVE installation remains one of the main barriers. Unlike consumer-oriented immersive technologies, these systems require dedicated physical spaces, multiple synchronized projection systems, tracking infrastructures, rendering workstations and highly customized installation procedures. Consequently, CAVE environments are generally found only in universities, research laboratories,

engineering centers, and specialized industrial organizations that can support both the initial investment and the long-term operational costs. Operational management further increases the complexity of these installations; managing a CAVE environment requires periodic projector alignment, stereoscopic calibration, synchronization of rendering systems, verification of tracking accuracy and regular hardware servicing. These activities demand specialized technical expertise that contribute to higher maintenance costs. Methodological constraints should also be considered. Considering that each CAVE installation represents a unique experimental infrastructure, experimental studies conducted in CAVE environments are often limited by the relatively small number of available installations, restricted participant samples and the organizational effort required to conduct repeated experimental sessions. This reduces opportunities for large-scale studies and makes multi-site validation more difficult to achieve. These developments, however, do not reduce the scientific value of CAVE technology. Instead, they have reinforced its role within application domains where its distinctive characteristics remain difficult to replicate using wearable devices. The relevance of CAVE technology should therefore be assessed in relation to the specific requirements of the application rather than through direct comparison with consumer-oriented immersive devices.

5.4 Future Applications

The future of CAVE technology is unlikely to depend on direct competition with consumer-oriented immersive devices. Instead, its long-term relevance will be determined by its ability to integrate with emerging digital technologies and to become part of broader immersive ecosystems. Rather than existing as isolated projection-based environments, future CAVE systems are expected to evolve into intelligent collaborative platforms capable of combining immersive visualization, artificial intelligence, digital twins, cloud infrastructures and multi-device interaction. One of the most promising developments concerns the integration of Virtual Reality

and Mixed Reality (MR). Rather than considering projection-based and wearable technologies as competing solutions, future immersive environments may combine the strengths of both approaches. CAVE installations could provide shared collaborative workspaces for groups of users, while MR headsets supply personalized information overlays, spatial annotations, or task-specific guidance. Such hybrid environments would preserve face-to-face collaboration while simultaneously extending the amount of contextual information available to each participant. Another important direction involves multi-device accessibility. Future immersive platforms are expected to support simultaneous interaction through heterogeneous devices, including CAVE systems, HMDs, tablets, augmented reality glasses and conventional desktop workstations. This interoperability would allow participants located in different physical environments to collaborate within the same virtual workspace, significantly increasing the flexibility of immersive applications. Future engineering reviews, medical planning sessions, emergency simulations, educational activities and scientific collaborations may combine projection-based visualization with wearable immersive devices, enabling each participant to access the same digital environment through the interface most appropriate for their role. A particularly promising application concerns the integration of CAVE systems with digital twin technologies. By connecting immersive visualization with real-time industrial data, sensor networks and predictive simulation models, future CAVE environments may become advanced decision-support platforms. Engineers and operators could visualize the current state of complex industrial assets, evaluate alternative operating conditions, predict future system behavior and collaboratively assess maintenance or production strategies before implementing real-world actions.

Artificial intelligence is expected to represent another major driver of future immersive environments. AI-driven adaptive interaction may enable virtual environments capable of continuously responding to participants' behavior,

physiological measurements, gaze direction, cognitive workload or emotional state. Machine learning algorithms could dynamically modify virtual scenarios, interaction complexity, virtual characters, and environmental conditions according to the participant's responses, creating highly personalized immersive experiences. Such adaptive systems can be particularly valuable in emotion research, psychological assessment, rehabilitation, professional training, and human factors studies, where individualized experimental conditions are often desirable. Finally, the future competitiveness of immersive technologies will increasingly depend on cross-platform interoperability. Open communication standards and interoperable software ecosystems will allow virtual environments to operate seamlessly across Desktop VR, HMDs, CAVE installations, digital twins and AI services. Such interoperability would reduce technological fragmentation while enabling organizations to select the most appropriate immersive technology according to the specific requirements of each application rather than being constrained by proprietary ecosystems.

Conclusion

In conclusion, this thesis discussed the history of virtual reality technologies, highlighting key stages of its evolution and technological aspects, its economic characteristics, potential and application areas, as well as its suitability for the research of human emotions, behavior, and decision-making process. The most frequently used indicators in the literature were identified in order to best evaluate CAVE emotional environments. The review of virtual reality technologies and discussion of their characteristics show that such technologies became increasingly more accessible, versatile and applicable to a variety of purposes and needs of both industries and individuals. Specifically, the analysis of desktop VR, Head-Mounted

Displays and CAVE technologies shows that all three technological paradigms offer a specific balance of the parameters of immersion, presence, accessibility and scalability. In terms of price, flexibility of deployment and accessibility, desktop VR represents a good option. Nevertheless, its limitations include low levels of immersion and engagement that make this solution rather weak in terms of research. Head-Mounted Displays technologies appear to be the most successful among other VR technologies. Indeed, HMDs offer excellent levels of immersion and presence combined with moderate implementation prices and scalable infrastructure. Their success can be explained not only by technological advancement, but also by the development of computer games, entertainment technologies, digital platform industries and by the expectations generated following attempts to capture the mass market with highly affordable solutions. At the same time, it should be noted that CAVE technologies still represent an interesting niche in the virtual reality ecosystem, which does not offer high levels of scalability and ease of implementation but possesses specific characteristics which make it a unique resource in the field of virtual reality like opportunity for immersive visualization, interaction with objects in the environment, natural navigation, participation in collaboration and direct observations of participants. The experimental paradigm developed within the frames of this thesis allows understanding the potential of CAVE technologies in terms of research. Thus, integration of cognitive tasks, emotional induction procedures, environmental interactions and decisions allow creating the conditions for the creation of realistic and emotionally rich situations in the context of high levels of experimental validity and control. When discussing the development of immersive technologies in the future, there is an obvious trend towards creation of complex hybrid ecosystems based on various technologies such as virtual reality, mixed reality, artificial intelligence, bio-sensing systems and simulation.

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