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Overview of Immersive Data Visualization: Enhancing Insights and Engagement Through Virtual Reality

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In recent years, the explosion of data has been immense, especially in terms of volume and velocity which poses a new challenge in the visualization of data and extracting patterns from it efficiently. Visualization is one the most critical aspects of data analysis as it also helps in the selection of an appropriate model for machine learning. However, this changes when we are dealing with complex data or hyper-dimensional datasets. 2D visualization of this complex or hyperdimensional dataset can be hard to visualize owing to the inherent loss of information due to spatial constraints which consequently hinders the extraction of meaningful patterns for the development of machine learning models. In recent years, there has been substantial advancement in immersive technologies like Virtual Reality, Augmented Reality, Mixed Reality and adoption in various sectors especially in gaming, entertainment, and training. However, when it comes to data analysis and data visualization, immersive technology is at an emerging stage but has promising potential. This review research paper, through a series of application domains, aims to uncover this promising potential of virtual reality by shedding light on its capabilities and its limitations in representing complex and hyperdimensional data to uncover new insights, pattern recognition, and decision-making processes.

Keywords: Data Visualization; immersive; virtual reality; data analysis; 3D visualization.

Introduction:

With the boom of the internet in the last two decades, the current rate of generation of data is so astronomical, now reaching 2.5 quintillion bytes per day (2.3 billion gigabytes per day) and increasing rapidly [1]. Consequently, this sheer volume of data gives rise to vast types of datasets. These datasets are characterized by complexity and hyper-dimensionality, containing numerical measurements, images (ImageNet), spectra (The Sloan Digital Sky Survey (SDSS)), time series (Global Historical Climatology Network (GHCN)), categorical labels, text (Google Books Ngram Viewer) etc. [2]. Complex data is a type of data that is difficult to analyze because it is heterogeneous, noisy or has a large number of dimensions, while hyperdimensional data contains a large number of features or dimensions. Hence, the complexity of data coupled with hyper-dimensionality makes it challenging to recognize patterns and extract insight from data. Moreover, there may be multivariate correlations so intricately entangled in datasets which may further complicate the process of pattern recognition. Data visualization is at the crossroads of opportunity and challenge. On one hand, there is an abundance of data that provides a rich source of information allowing data analysts to find patterns and valuable insights. On the other hand, handling these complex and hyperdimensional datasets requires novel tools and techniques that efficiently handle the complexity and hyperdimensional datasets [3].

Human brains are inherently adept at recognizing and processing three-dimensional data. However, it is only in the past 50 years that we have trained ourselves to work with two-dimensional interfaces. Despite our proficiency with flat screens, our brains function far less efficiently with 2D data, limiting the scale and complexity of what we can analyze compared to 3D environments. As the volume of data generated doubles every two years, immersive visualization becomes increasingly critical, allowing vast amounts of information to be displayed and ingested with less effort. Originally designed for gaming and entertainment, VR has proven to be highly effective for data visualization, transforming tedious and time-intensive tasks into simple, playful, and fast experiences. For example, in biomedical applications, VR allows for high-resolution visualization of protein structures within single cells, facilitating detailed exploration of cellular architecture and aiding in the understanding of complex biological processes. In military training, VR provides realistic simulations of battlefield scenarios, enhancing navigational and coordination skills through interactive and scalable environments. For brain data analysis, VR integrates various data types into a comprehensive 3D model, enabling nuanced analysis of brain functions and aiding in disease detection [4].

The human mind is naturally good at recognizing patterns and correlations between variables, which is crucial in data-driven science. However, effective, and flexible visualization is essential for this process. In the 21st century, the abundance of data presents a significant challenge for meaningful visual exploration. Hyper-dimensional data is challenging to visualize as humans are programmed to see the world in 3D. Projecting high-dimensional data into lower dimensions often results in significant information loss and ineffective data visualization. To effectively visualize hyperdimensional data, additional dimensions are necessary to recognize interesting patterns, correlations, and outliers. Emerging technologies such as Augmented Reality (AR) and VR, known as immersive technologies, are being explored to unlock new possibilities in data visualization. Although the concept of using immersive technologies for data visualization and analysis is not new [4] and was proposed in the early nineties, recent technological advancements have made immersive hardware and software more affordable and powerful. VR holds significant promise for dealing with complex datasets where variables are highly correlated, and the information space is spatially intricate and dynamic over time. These challenges often arise in fields such as engineering, atmospheric sciences, and physical sciences, referred to as "Grand Challenge problems." VR addresses these issues by providing immersive 3D environments that enable high-resolution visualization and interactive exploration of data. By leveraging depth perception, Interactive navigation, and immersive engagement, VR mitigates information loss and spatial constraints. This enhanced interaction leads to better pattern recognition, improved data comprehension, and more effective communication of complex ideas. Therefore, VR is not just a tool for entertainment but a powerful medium for transforming how we visualize and analyze data, making it an essential asset in today's data-driven world. This paper presents a unique exploration of immersive data visualization techniques using Virtual Reality (VR) for high-dimensional data sets. The novelty lies in applying VR to uncover patterns and trends across diverse fields such as healthcare, business, and crime analysis. This study offers new insights into the capabilities and limitations of VR as a tool for immersive visualization, highlighting its potential to represent complex datasets, reveal hidden patterns, and enhance the decision-making process through an engaging and interactive visual experience.

Objective:

This review paper aims to provide a comprehensive overview of the potential of immersive technologies, particularly virtual reality (VR), in enhancing data visualization and analysis. By examining various application domains, the paper seeks to demonstrate how VR can address the challenges associated with complex and hyperdimensional datasets, improving the ability to uncover patterns and enhance user engagement. The ultimate goal is to illustrate how VR can facilitate more accurate and confident data-driven decision-making.

Related Work:

Immersion:

The concept of immersion involves the interaction of humans with an environment. The environment could be computer-generated such as virtual reality (VR), augmented reality (AR), or mixed reality (MR). Generally, immersion often removes the barriers between data and analysts enhancing the process of data analysis [5]. Immersion is often separated into "psychological" (relating to the user's psychological state, engagement, emotion, and perception) and "technological" aspects (pertaining to the environment's visual and interaction capabilities). Spatial immersion is another term used, involving a first-person 3D view of the environment, often associated with virtual reality experiences. It can also apply to spatial augmented reality, where digital projections interact with the real world [6]. Various studies explore immersion in different contexts, and it can be subjectively and objectively measured. However, there is some confusion and debate surrounding its precise definition and scope. It could be as simple as reading a book to complex multi-modal interactions.

Immersive Data Visualization:

The term "visualization" has long been used in various contexts with different meanings even before it was formally established as a scientific field. In the realm of immersive environments, visualization takes on a more diverse and dynamic character, as it encompasses a wide range of structures and types that can be presented. Immersive visualization serves as a convergence point for various research areas, enabling the representation of data in multiple formats such as 3D models, 3D graphs and plots, simulations, and various 2D representations [7]. Immersive Virtual Reality (iVR) employs tracking sensors for real-time motion tracking via 3D glasses or head-mounted displays (HMDs). It projects the virtual realm onto surfaces and HMDs by continuously monitoring the user's head orientation and position. This enables users to physically move within the virtual world, offering a sense of bodily presence through visual changes and physical actions. iVR supports geospatial data visualization, integration, manipulation, and querying through embodied experiences. Researchers can explore Earth and solar system locations, gaining insights from expanding 3D data sets [8].

The potential applications of immersive visualization are extensive, as it can be employed to visualize data from diverse sources such as statistics, medicine, computer sciences, heritage, and many others. This technology-driven domain incorporates elements beyond pure data representation, delving into the realms of multisensory interfaces, interactive features, navigation techniques, collaborative aspects, and advanced rendering techniques. Additionally, immersive visualization caters to domain-specific subjects, making it a versatile and adaptable tool for exploring and analyzing data in various fields and industries.

Need for Immersive Visualization:

Data visualization has taken on growing importance in light of the increasing complexity and quantity of data, necessitating engaging and informative experiences for both general and professional users. Its utility spans various objectives, including enabling deeper comprehension, expediting decision-making, and ensuring that users remain at the forefront of data and insights [9]. Immersive technologies have a substantial impact on the decision-making process by simplifying data complexity, allowing for swift and precise decision-making through visual data mining techniques that harness human perception [10]. Scientific visualizations are essential for information sharing and learning among researchers, businesses, and government organizations. Immersive visualizations are preferred for multi-dimensional applications like stock analysis or sports analytics, interactive entertainment and gaming experiences, and industrial applications such as healthcare and enterprise training, due to the sense of physical presence they provide [11]. Augmented and virtual reality have evolved into multi-dimensional realms, encompassing presence, interactivity levels, and suitable embodiment devices. These immersive technologies, with their fidelity to human spatial, visual, and aural senses, are highly suitable for complex data and information visualization [12]. A summary of the methods for immersive data visualization has been shown in Table 1.

Material and Methods

This study explores the potential of immersive visualizations in virtual reality (VR) to enhance data visualization and analysis, particularly for complex and hyperdimensional datasets. We employ a systematic approach to examine VR's capabilities and limitations, drawing insights from various application domains.

Research Questions

The primary questions of this study are:

- **RQ1:** How VR can tackle challenges posed by complex and hyperdimensional datasets.
- **RQ2:** What methodologies/theories are being used to research VR visualization? To evaluate the effectiveness of VR in enhancing engagement and data understanding.
- **RQ3:** What are the existing approaches and techniques?

Systematic Literature Review:

To achieve these objectives, we conducted a systematic literature review (SLR) to gather and analyze relevant studies on VR visualizations. The review process included the following steps:

Database Selection:

We selected seven primary academic databases to identify relevant research: ACM Digital Library, IEEE Xplore, SpringerLink, ScienceDirect, Google Scholar, Elsevier, and MDPI.

Search Query Construction:

The search terms included combinations of 'virtual reality' and 'visualization' along with related terms like 'data visualization,' 'information visualization,' and 'immersive visualization.'

Search Execution:

The search was carried out between December 2023 and January 2024, covering publications from 2018 to 2023.

Inclusion Criteria:

Publications from 2018 onwards, journal articles, conference proceedings, and scientific magazines, studies focusing on VR visualization and its indicators were included.

Exclusion Criteria: Online presentations, papers not addressing visualization elements or techniques, and research focusing solely on non-visual stimuli unless combined with visualizations.

Selection Process:

Initial assessment based on titles and abstracts, followed by full-text reading and critical appraisal to validate studies, resulting in 153 relevant papers, with 62 identified as primary sources.

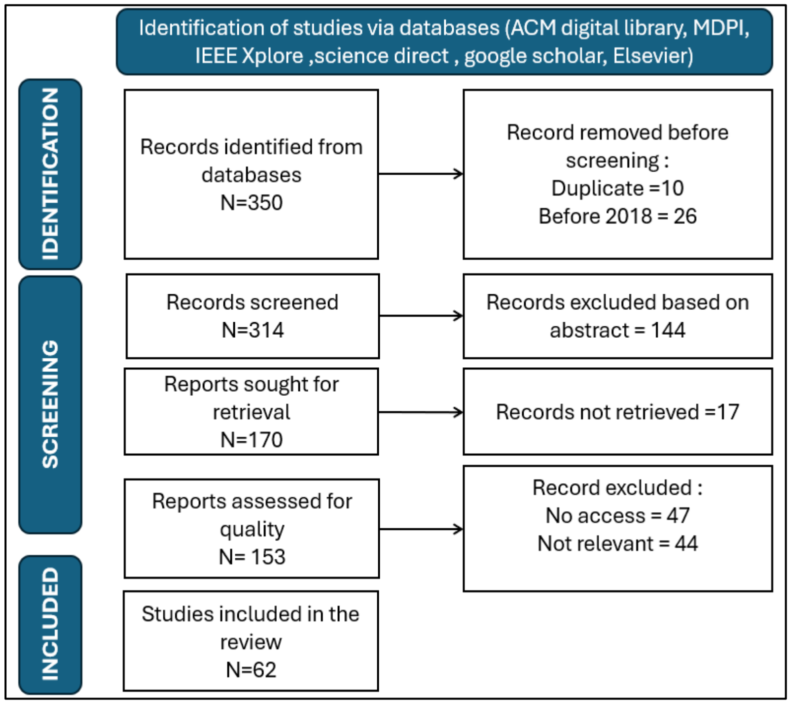

Figure 1: PRISMA Flow Diagram for systematic records selection.

The PRISMA Flow Diagram (Figure 1) illustrates the systematic process of record selection and the stages involved in identifying the final set of relevant studies.

Types of Contributions:

The reviewed papers were categorized based on their contributions to theoretical frameworks, evaluation and design concerns, and empirical studies. This study offers new insights into the capabilities and limitations of VR as a tool for immersive visualization, highlighting its potential to represent complex datasets, reveal hidden patterns, and enhance the decision-making process through an engaging and interactive visual experience.

Data Analysis and Synthesis:

The selected studies were analyzed to identify the preferred visualization types and structures, methodologies, research gaps, existing approaches, and selected software and hardware for VR visualizations. This analysis aims to provide a comprehensive overview of VR's role in data visualization and identify opportunities for future research. By following this systematic approach, this study aims to contribute to the understanding of VR's role in data visualization, highlighting its potential to enhance insights and engagement through immersive experiences. By following this systematic approach, this study aims to contribute to the understanding of VR's role in data visualization, highlighting its potential to enhance insights and engagement through immersive experiences [13].

Results:

Interactive Multidimensional Data Visualization (MDV):

Interactive Multidimensional Data Visualization (MDV) has been widely investigated in the fields of Information Visualization and statistics, and research in this area continues to evolve. One approach involves the use of dimension reduction techniques, such as Multidimensional Scaling (MDS) [13], to represent high-dimensional data points in 2D or 3D scatterplots while preserving their distances and revealing clusters and outliers. However, it's important to note that MDS, like other reduction methods, can result in some information loss and may pose challenges for individuals who are not experts in the field. Adaptations of conventional visual representations have been created to display multiple data dimensions through small multiple views. This technique, widely used in Business Intelligence (BI) software [14], facilitates the intuitive exploration of multivariate data. Scatterplot matrices (SPLOMs) present all possible 2D combinations of data dimensions in a matrix, aiding users in identifying patterns between pairs of dimensions (referred to as "Scatterplot Diagnostics" or Scagnostics, as termed by the Tukeys [15]). Nevertheless, with an increase in dimensionality, the utility of SPLOM views becomes limited due to space constraints on conventional desktop displays.

Parallel Coordinates Plots (PCPS):

Parallel Coordinates Plots (PCPs) are used to visualize data across multiple dimensions through parallel axes [16]. In this representation, each data point is depicted as line segments that intersect each axis at specific attribute values [17]. Unlike Scatterplot Matrices (SPLOMs), PCPs reveal relationships between only the adjacent axes, providing a distinct way to explore multivariate data. To mitigate clutter in displays containing high-dimensional datasets, interactive methods are crucial for data filtering and exploration. Focus+context techniques, such as brushing and linking, help emphasize subsets of data across different visualizations [18]. Animations can also enhance the understanding of correlations between dimensions [19], like using 3D rotation to transition between 2D visualizations in a scatter plot matrix [19].

ImAxes:

ImAxes represents an immersive system designed for the exploration of multivariate data through seamless, modeless interaction. The fundamental component of ImAxes is embodied data axes, which users can interact with as tangible objects within the immersive environment. Through the combination of these axes, intricate visualizations are formed, driven by their closeness and relative alignment. These visualizations are described using formal grammar. This intuitive composability leads to the emergence of numerous visualizations and interactions [20].

Application Domains:

Visualizing Complex Protein Images in Single Cell in 3D Multiplex View:

In biomedical applications, Head-Mounted Displays (HMDs) and Virtual Reality (VR) are harnessed for 3D visualization. Computation platforms such as Unity can be employed to create software packages tailored for 3D dataset visualization in VR. An instance of such software is ConfocalVR, developed by Immersive Science [21]. This software empowers users to delve into cellular architecture and explore the distribution of proteins and molecules through immersive 3D visualization. The dataset used for visualization comprises 3D subcellular co-detection by indexing (CODEX) images, which were obtained through multiplex imaging using DNA-barcoded antibodies targeting 20 cellular markers [22]. These CODEX data were collected with a spinning-disk confocal microscope equipped with a 60x objective lens, resulting in high-resolution optical images spanning 25-30 depth slices of a 5-mm cancer tissue sample (Figure 1). The visualization efforts were centered on three distinct regions within a microarray sample, each containing single-cell distributions from individuals with chronic lymphocytic leukemia (CLL), Hodgkin's lymphoma (HL), and natural killer (NK)/T cell lymphoma. Image processing algorithms were applied to perform background subtraction and registration, ultimately leading to images stored in the Tag Image File Format (TIF or .tif). Subsequently, the TIF files were converted into the Neuroimaging Informatics Technology Initiative file format (NIfTI or. nii) using ImageJ. The final step involved using the ConfocalVR software for the immersive 3D visualization of these datasets.

Military Training Uses Immersive Technology to Simulate Battleground:

Military training employs virtual reality to simulate battlefield scenarios and instruct in strategic tactics through interactive training. These VR simulations enhance soldiers' navigational and coordination abilities by immersing them in an interactive environment. In contrast to conventional methods, these simulations offer a more precise depiction of warfare scenarios and complex situations (Figure 3). Additionally, they provide scalability and flexibility in the training content [23].

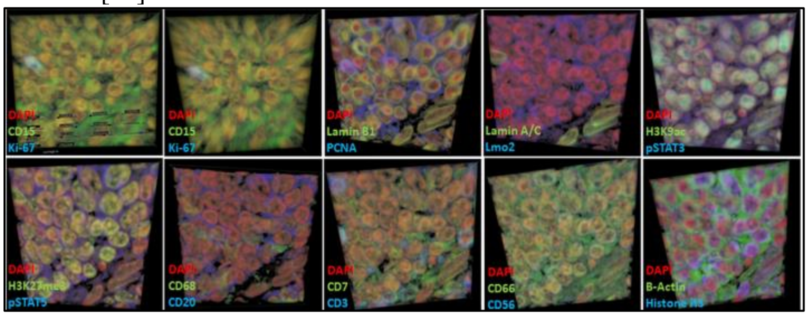

Figure 2: Visualizing Multiplexed Protein Imaging Data in Virtual Reality (VR). The image showcases the visualization of highly multiplexed CODEX imaging data containing 18 markers, which were acquired from individuals with chronic lymphocytic leukemia (CLL) using ConfocalVR [20].

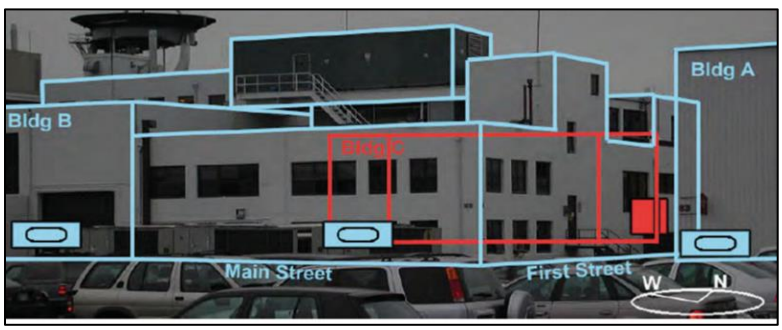

Figure 3: Military training simulation example, using Virtual Reality [22].

Augmented reality (AR) is a handy tool in military operations for providing real-time context-aware information. It is achieved through head-mounted AR glasses or handheld devices like smartphones. AR assists with remote assistance and recreating specific environments, like a demolished structure. It enhances understanding of minor and vital details in the actual environment, aiding rapid decision-making in combat. AR headsets also deliver navigation information to guide personnel, ensuring a seamless experience [24].

Brain Data Analysis Using Immersive Technology:

Brain data analysis involves multiple aspects, including brain anatomy, structure, function, and temporal activity. Data sources include EEG, fMRI, DTI, MRI, CT, and PET. The goals are understanding brain function, detecting diseases, comparing cohorts, and correlating behavior with brain activity. Spatial and abstract data can be combined using S3D representations and abstract visualizations. Immersive environments aid in data analysis and preprocessing.

Abstract Data:

Visualizing three-dimensional spatial data in spatial 3D (S3D) environments is a logical choice [25]. However, the value of using S3D visualizations for abstract data requires more explanation. While there have been reservations within the data visualization community, there are notable advantages to visualizing abstract data in Interactive Environments (IE), especially when combined with spatial data. Recent research has shown [26] the potential of S3D visualizations for exploring and analyzing abstract data, such as high-dimensional data after dimensionality reduction, or networks. Networks are of particular interest in the field of Information Architecture (IA) due to their wide application in modeling and representing data for communication and analysis.

Networks lack inherent spatial structure or direction, allowing for flexible design of visual representations using metaphors like node-link or matrix. The node-link metaphor is better suited for a 3D representation (Figure 5). Common layout techniques for networks involve positioning nodes and routing edges using methods like force-directed layouts. These techniques can be extended to work in three dimensions. However, optimizing certain goals in 3D layouts, like distance representation, doesn't guarantee improved readability due to issues like perspective-dependent occlusion and distortion.

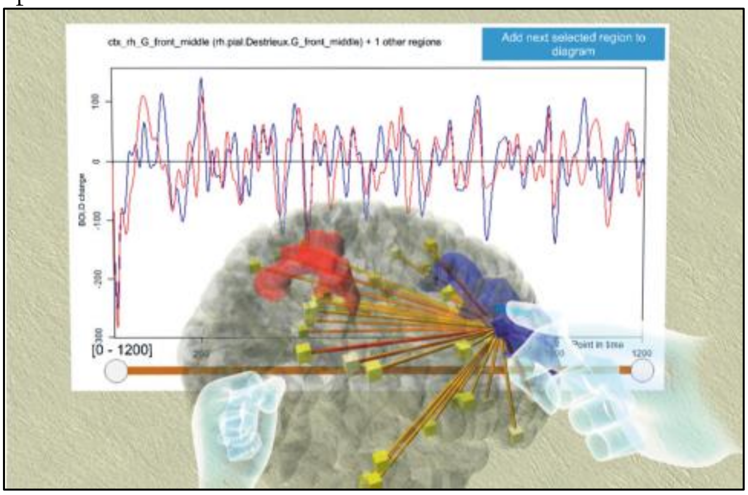

Figure 4: Brain data analytics involves combining a brain model capable of distinguishing anatomical regions with brain activity data. The acquisition of activity data generates time series that can be represented in traditional charts but can also be transformed into a network through correlation analysis. This network mapping enables the visualization of activity correlations between regions within the 3D model. Users can interact with the model by rotating it and selecting specific regions for in-depth analysis of their activity and correlations [27].

Figure 5: The study explores the preservation of mental maps in node-link network visualization, where users interact with an immersive 3D network visualization in Virtual Reality (VR) [28].

Navigating large-scale networks in a 3D space presents challenges that need further exploration. This requires understanding how mental maps are created, orientation within networks and S3D representations, and evaluating methods for traversing these representations. In summary, S3D visualizations offer unique possibilities for exploring abstract data, particularly in combination with spatial data, although challenges in readability and navigation need more investigation.

Crime Data:

In recent years, there has been a significant amount of research focused on predicting criminal activities. In 2020, the FBI collected crime statistics from a large number of law enforcement agencies across the country, providing insights into the extent of criminal occurrences [29]. The increasing frequency of crimes has become a major concern for law enforcement agencies, security organizations, and the general public. Police officers play a crucial role in maintaining law and order, and crime analysis involves compiling all reported criminal incidents into a comprehensive report. This consolidated report aids in decision-making and the implementation of strategies to control and prevent crimes [30].

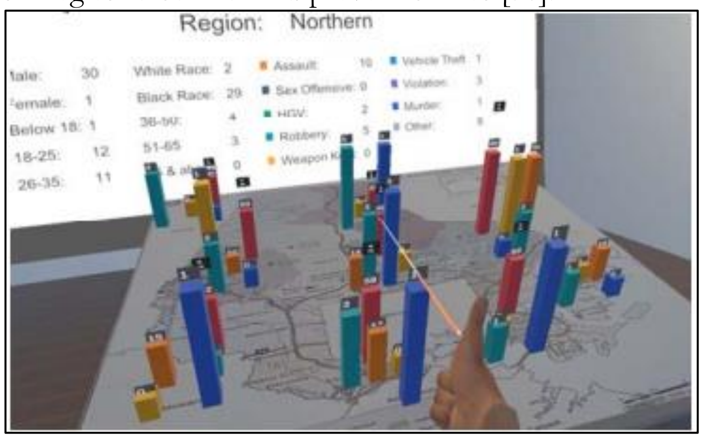

Figure 6: This is a depiction of the Data Visualization tool designed for Baltimore crime data, which is accessible through immersive Virtual Reality (VR) [31].

Additionally, Figure 7 further underscores the potential of such systems, empowering security personnel to select specific charge types. This capability offers a nuanced approach to monitoring and response strategies, tailored to the distinct nature of criminal incidents.

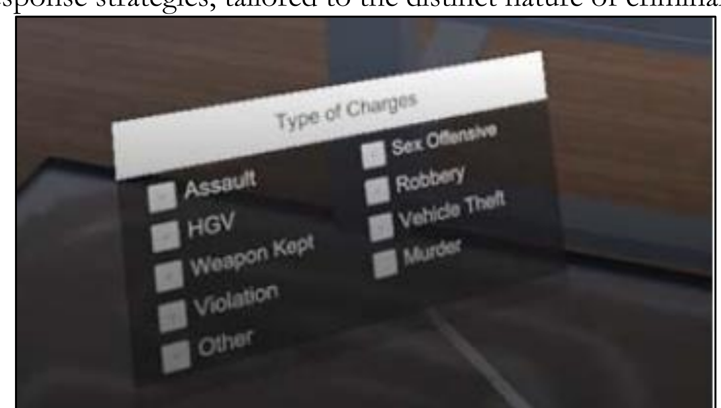

Figure 7: Menu selection options for the officers.

One innovative approach to comprehending crime trends and facilitating predictive modeling is using immersive virtual environments. These environments simulate realistic settings, providing users with an experience that closely resembles reality. Immersive environments are particularly useful when dealing with vast amounts of crime data. By immersing users in this environment, they can gain a deeper understanding of critical areas and interpret charts and graphs more effectively. This modern approach allows users to interact with and explore the virtual environment in ways that were not possible before, potentially leading to novel insights into our interaction with reality.

The concept of an immersive environment is depicted in Figure 6, which illustrates how selecting specific regions can filter data to display records related to that particular area. This type of visualization aids in conveying information more clearly and helps users grasp patterns and correlations within the data.

Observations:

As discussed above, traditional 2D visualization methods often suffer from information loss and spatial constraints, making it challenging to fully comprehend intricate data structures. VR addresses these issues by offering high-resolution 3D visualizations that provide a deeper understanding of data. For instance, in biomedical applications, VR allows for detailed exploration of cellular architecture, enabling users to interact with 3D models of protein distributions within single cells. This immersive exploration helps in understanding complex biological processes and disease mechanisms. In military training, VR simulations create realistic and interactive battlefield scenarios, enhancing navigational and coordination skills through scalable and flexible training environments. For brain data analysis, VR integrates spatial and abstract data into a single 3D model, facilitating detailed study of brain anatomy and activity, which is crucial for detecting diseases and understanding brain functions.

VR also excels in visualizing abstract data and large-scale networks by providing spatial representations that help users intuitively understand relationships and structures within the data. This is particularly useful for exploring high-dimensional data or complex networks that lack inherent spatial structure. For crime data visualization, VR offers immersive environments that allow interactive exploration and filtering based on specific regions or crime types, aiding in predictive modeling and strategic decision-making. By leveraging the unique capabilities of VR, such as depth perception, interactive navigation, and immersive engagement, users can achieve a more comprehensive and intuitive understanding of complex datasets. This enhanced interaction leads to better pattern recognition, improved data comprehension, and more effective communication of complex ideas. VR's ability to create shared virtual workspaces also facilitates collaborative analysis, making it easier for teams to discuss insights and make collective decisions regardless of their physical location.

Technical Challenges:

Constraints in VR experiences are attributed to headset quality, software applications, and interactivity issues. Inadequately designed software applications can induce motion sickness in users. These identified issues could be mitigated by investing in research and development to improve the quality of VR headsets, with a focus on the display resolution, comfort, and reducing motion sickness. Additionally, conducting user studies to understand motion sickness triggers and designing software with features that mitigate discomfort can contribute to a more user-friendly VR environment. Standalone wireless headsets face limitations related to processing power, weight, field-of-view, and battery life. Presently, interactivity is confined to controllers and hand gestures, and these interfaces are still in the developmental stage. Setting up and affording high-end PC-based VR headsets can be challenging. Investing in research for more natural and intuitive interfaces, such as advanced haptic feedback, eye-tracking, and voice recognition, aims to enhance user interactivity.

Augmented reality experiences on AR glasses are constrained by design, size, weight, battery life, and field of view. Smartphone-based AR experiences lack rich, immersive interactions and depend on specific smartphone models and hardware capabilities. Addressing these challenges involves fostering collaboration across the AR and VR ecosystem, including hardware manufacturers, software developers, and content creators. Encouraging the development of diverse and high-quality content, as well as investing in software development to enhance smartphone-based AR interactions and exploring partnerships with smartphone manufacturers to standardize AR capabilities across devices, are potential solutions.

Business Challenges:

Limited awareness of VR and AR technology among businesses and consumers may stem from factors such as customer readiness, high costs, and challenges in the ecosystem's maturity, including hardware, software, and content availability. To tackle these issues, initiate marketing campaigns, workshops, and educational programs aimed at increasing awareness among businesses and consumers about the potential applications and benefits of AR and VR. Develop educational content and outreach programs to enlighten consumers about the value and possibilities of AR and VR, spotlighting real-world use cases and benefits. Foster collaboration across the AR and VR ecosystem, involving hardware manufacturers, software developers, and content creators, and champion the development of diverse and high-quality content.

Conclusion:

Applications of VR and AR deliver superior visualizations compared to traditional methods, resulting in enhanced decision-making, cost savings for organizations, and improved consumer experiences. Businesses can attain a competitive advantage, enhance brand value, strengthen stakeholder communication, and increase client satisfaction by offering immersive products. In certain cases, cost reduction is also achievable. Despite these advantages and the rapid progress in the field, there are short-term challenges in implementing immersive visualizations. To address these challenges, solution providers must design products and services that provide the appropriate level of presence, interactivity, and immersion, tailored to the specific application. A human-centered design approach should be adopted, incorporating more human senses, as AR and VR harness visual, auditory, and spatial dimensions to create effective experiences.

Table 1: Summary of various methods for immersive data visualization

Method	Description	Benefits	Limitations	Technologies	References
Virtual Reality (VR)	Uses headsets to create fully immersive, 3D virtual environments where users can interact with data.	Enhanced spatial understanding, Increased engagement,360-degree exploration, Natural interactions, Isolates from distractions	Requires specialized hardware and software, Potential for simulator sickness, Limited collaboration capabilities	Oculus Quest 2, Valve Index, PlayStation VR2	[32], [8]
Augmented Reality (AR)	Overlays digital information onto the real world, allowing users to visualize data in context.	Blends virtual and real worlds, no need for headsets, supports physical interactions with data, Facilitates collaboration	Limited field of view, can be affected by lighting conditions, Dependency on device compatibility	Microsoft HoloLens 2, Magic Leap 1, Google Glass Enterprise Edition 2	[33], [34]
Large-scale Displays	Uses large screens or projections to create shared immersive experiences for multiple users.	High-resolution visuals support collaborative exploration, no need for headsets, Promote group discussion	Requires dedicated space, Limited interactivity, Potential for visual fatigue	Wall-sized curved displays, projection domes, multi-touch tables	[35]
Haptic Feedback	Provides tactile sensations to enhance the sense of touch and interaction with data.	Improves understanding of physical properties, provides additional sensory feedback, Enhances realism	Limited availability, requires specialized hardware, can be distracting if not implemented well	VR gloves with haptic feedback, haptic vests, force feedback joysticks	[36], [37]
Spatial Audio	Uses sound to create a sense of depth and spatial awareness, guiding attention and enhancing data perception.	Increases immersion, provides directional cues, can convey information non-visually	Requires specialized audio equipment, can be affected by ambient noise	Object-based audio rendering, binaural audio, 3D soundbars	[38], [39]
CAVE(Cave Automatic Virtual Environment)	Multiuser Immersive Virtual Reality with cube-shaped spaces where walls, floor, and ceilings are projected screens.	High-Resolution graphics Multi-user capability, Real-time interaction, enhanced data visualization.	Limited Physical Space, Costly, Calibration challenges, Motion sickness	CAVE, CAVE2. Barco cave display, ICUBE	[40], [41]

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