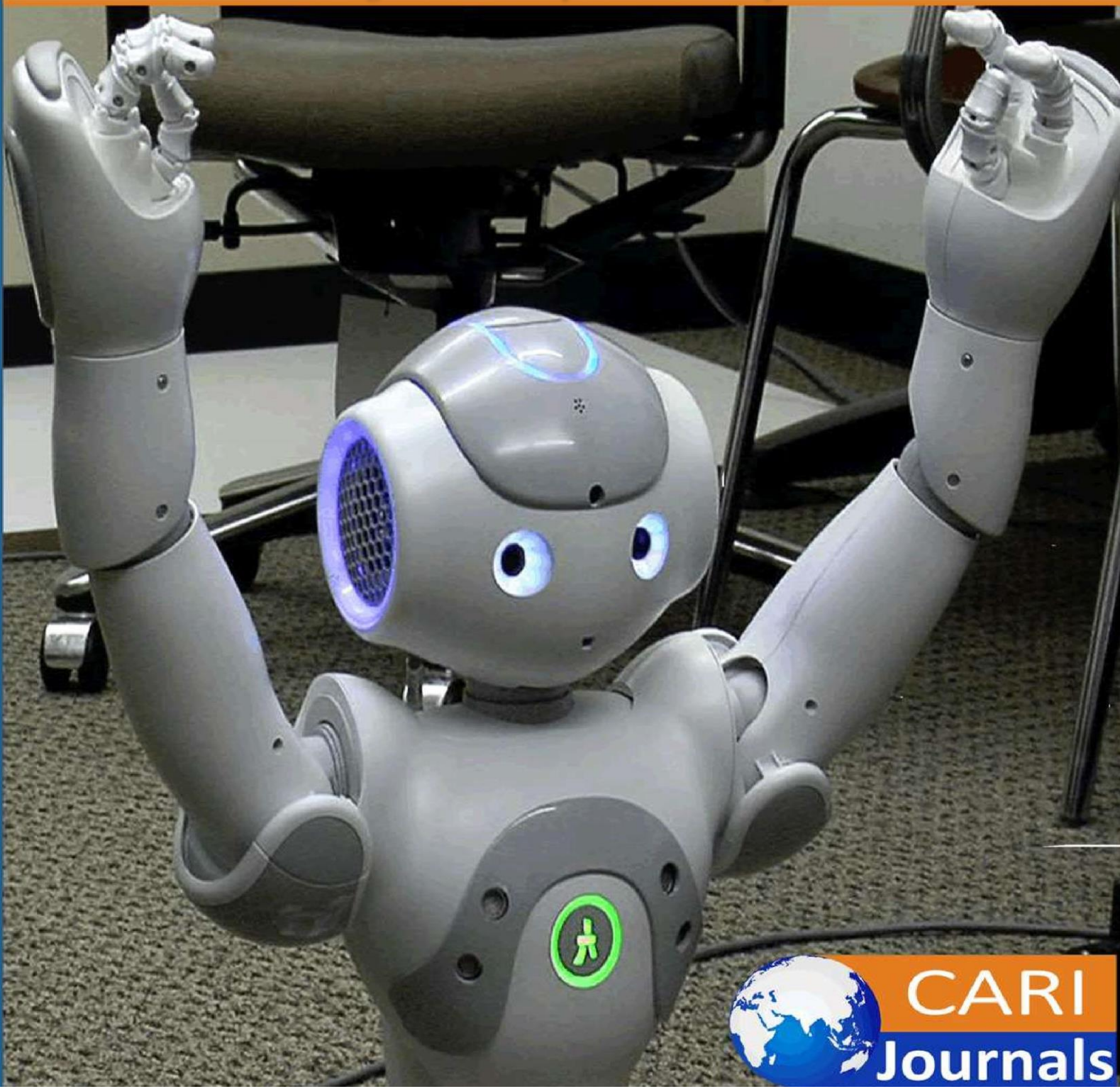


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**Beyond the Screen: Immersive Analytics with  
Augmented Reality/Virtual Reality**



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## Beyond the Screen: Immersive Analytics with Augmented Reality/Virtual Reality

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### Abstract

Immersive analytics is a paradigm shift in data visualization that uses Augmented Reality and Virtual Reality technology to build three-dimensional spaces in which the user can intuitively explore complex data sets by spatial awareness and physical interaction methods. The replacement of traditional two-dimensional interfaces with immersive environments is the basic limitation of traditional analysis tools, which are replaced by unified environments that allow analysts to simultaneously have a global perspective of data patterns and drill down to areas of focus. Recent advancements in WebXR APIs and frontend frameworks have allowed for advanced cross-platform solutions that connect web technologies with various AR/VR hardware systems, enabling browser-based immersive analytics applications without the need for specialized software installations. Comprehensive assessment in scientific, educational, and industrial sectors shows uniform enhancements in spatial awareness, pattern detection, and teamwork in problem-solving tasks when contrasted with conventional dashboard interfaces. Technical architecture executions integrate sophisticated rendering pipelines, multi-modal interaction frameworks, and performance enhancement strategies that facilitate real-time handling of extensive datasets in resource-limited settings. Applications include molecular visualization, climate modeling, business intelligence, and educational settings, demonstrating improved analytical efficacy via physical interaction methods and three-dimensional data displays. Nonetheless, considerable obstacles persist, such as hardware restrictions, accessibility issues, integration difficulties, and organizational resistance that affect the broad implementation viability in both enterprise and educational settings.

**Keywords:** *Immersive Analytics, Augmented Reality, Virtual Reality, Data Visualization, WebXR*



## 1. Introduction

The evolution of data visualization methodologies has reached a critical juncture where traditional two-dimensional interfaces no longer adequately serve the complex analytical needs of modern organizations and research institutions. Immersive analytics emerges as a transformative approach that fundamentally redefines the relationship between users and data by creating three-dimensional environments where information becomes spatially embodied and naturally interactive [1]. This paradigmatic shift moves beyond conventional screen-based limitations to establish data exploration spaces that leverage human spatial cognition and natural interaction patterns. This enables analysts to navigate complex datasets through intuitive movements and gestures within virtual or augmented environments. Contemporary developments in spatio-data coordination have demonstrated remarkable potential for enhancing analytical workflows through tangible interaction mechanisms integrated with immersive visualization systems. Research findings indicate that spatial coordination frameworks enable seamless transitions between abstract data representations and physical interaction modalities, creating hybrid analytical environments where users can manipulate virtual data objects through natural hand movements and spatial gestures [1]. These coordination systems create two-way communication pathways between immersive visualization screens and physical interface devices, enabling concurrent multi-modal data exploration that merges the visual depth of three-dimensional settings with the tactile responses of real-world controllers. The combination of Augmented Reality and Virtual Reality technologies with cutting-edge frontend development frameworks signifies an important technological merger that has created fresh opportunities for developing complex analytical applications. Modern web-centric immersive technologies facilitate the instant rendering of complex three-dimensional data architectures while maintaining compatibility across diverse hardware devices, from independent headsets to mobile augmented reality tools. This innovation has enabled the development of browser-based immersive analytics tools that can handle and display large datasets without requiring specialized software installations or dedicated computing power. Visual analytics techniques have seen significant improvement in addressing the distinct challenges and possibilities offered by immersive settings. The analytical process within immersive contexts involves iterative cycles of data exploration, hypothesis formation, and insight validation that benefit from the enhanced spatial reasoning capabilities afforded by three-dimensional visualization [2]. These processes integrate automated analytical algorithms with interactive visualization techniques, creating synergistic relationships where computational analysis informs visual representation while user interactions guide algorithmic processing priorities. Conventional analytical interfaces place a heavy cognitive load on users, who need to mentally piece together multidimensional relationships from disjointed two-dimensional displays scattered across various screens or dashboard panels. These traditional methods frequently lead to information silos, making it difficult for analysts to stay aware of global patterns while investigating local anomalies or trends. The analytical workflow in traditional systems frequently requires users to alternate

between different visualization modes, creating discontinuous exploration patterns that can interrupt analytical reasoning and impede insight discovery processes. Immersive analytics addresses these fundamental limitations by providing unified three-dimensional spaces where complex datasets can be explored through natural navigation patterns that mirror real-world spatial exploration behaviors. The analytical challenges inherent in traditional approaches dissolve within immersive environments where users can simultaneously maintain global awareness of data patterns while focusing on specific regions of interest through intuitive zooming and filtering operations [2]. These environments support collaborative analytical sessions where multiple users can share the same immersive space, enabling distributed teams to conduct synchronized data exploration activities that would be impossible using conventional screen-based interfaces.

## 2. Theoretical Framework and Literature Review

The evolution of data visualization techniques has experienced significant changes that mirror wider technological progress and shifting user demands in analysis contexts. Early visualization methods focused on static graphic representations that offered fixed views of datasets, restricting analytical tasks to set perspectives and narrowing the range of exploratory analysis. The rise of interactive visualization systems brought dynamic manipulation features that allowed for real-time data filtering, perspective modification, and multi-view coordination, laying the groundwork for more advanced analytical workflows. Modern visualization studies have evolved from conventional screen-based formats to investigate immersive settings that utilize three-dimensional spatial displays and intuitive interaction methods. The shift from static graphs to interactive dashboards marked a major leap in analytical functionality, incorporating coordinated multiple views, brushing and linking methods, and real-time data integration that changed passive data observation into active investigation processes. The current transition toward immersive analytics environments represents the culmination of this evolutionary trajectory, where spatial computing technologies enable users to inhabit data spaces and interact with information through embodied manipulation techniques. Holographic visualization technologies have demonstrated remarkable potential for enhancing analytical effectiveness through tangible interaction mechanisms integrated with three-dimensional data representations. Research investigations into handheld holographic displays reveal significant improvements in spatial understanding and pattern recognition when users can physically manipulate virtual data objects within augmented reality environments [3]. These tangible augmented reality systems enable direct manipulation of three-dimensional visualizations through natural hand gestures, creating intuitive interfaces where abstract data concepts become physically graspable entities that can be rotated, scaled, and repositioned according to analytical requirements. Interactive exploration methodologies within immersive environments have shown measurable advantages over traditional visualization approaches, particularly for tasks involving complex spatial relationships and multi-dimensional data analysis. Empirical studies demonstrate that users exhibit enhanced performance in pattern identification, outlier detection, and trend recognition when engaging with three-dimensional

holographic visualizations compared to conventional flat-screen displays [3]. The effectiveness of these immersive approaches stems from the alignment between natural human spatial cognition processes and the three-dimensional representation of abstract data structures, reducing cognitive overhead associated with mental mapping between dimensional representations. Design study methodologies have emerged as essential frameworks for systematically evaluating and refining immersive analytics implementations across diverse application domains. Comprehensive design study approaches involve iterative cycles of problem characterization, abstraction development, solution design, and validation testing that ensure immersive analytics systems address genuine analytical needs rather than technological novelty [4]. These methodologies emphasize the importance of understanding domain-specific requirements, user workflow patterns, and task complexity factors that influence the effectiveness of immersive visualization solutions.

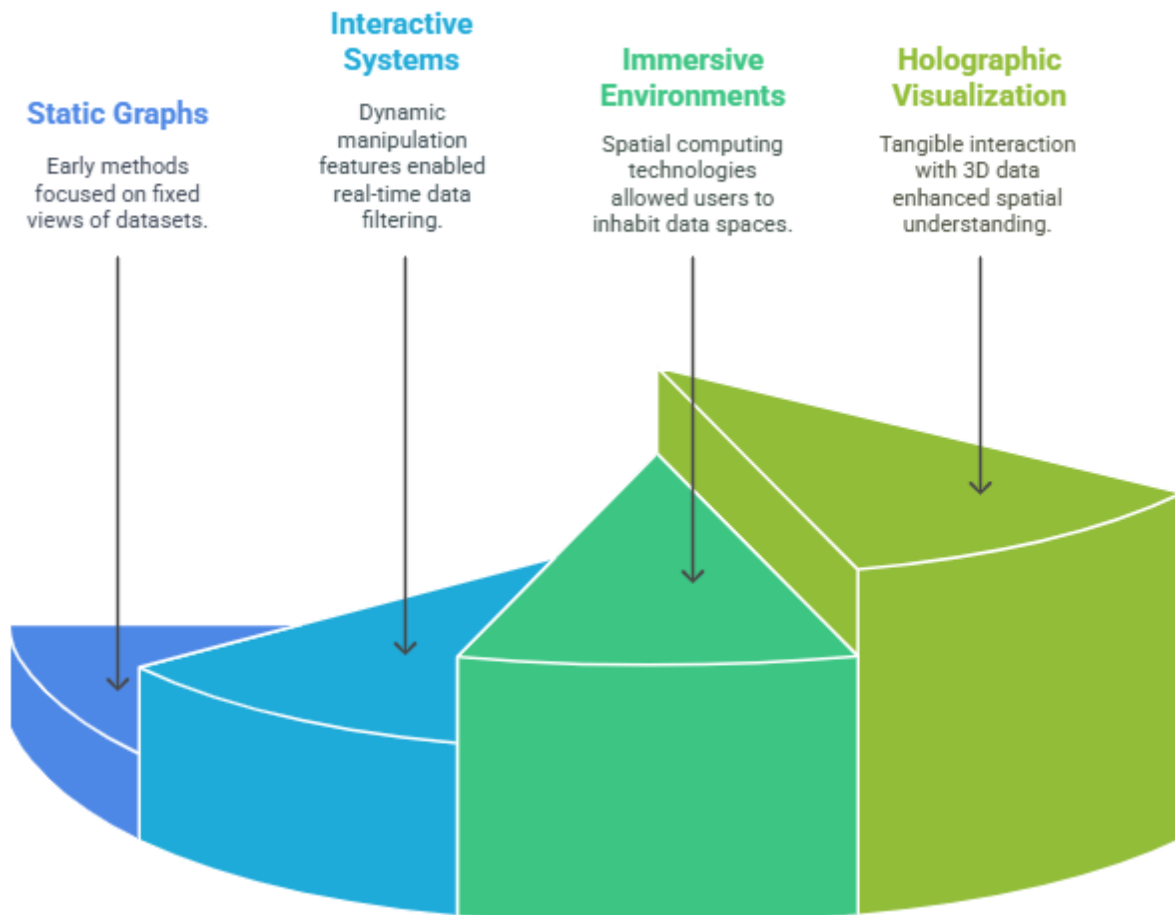


Fig 1: Evolution of Data Visualization [3,4]

Methodological reflections from extensive design study implementations reveal critical insights about the challenges and opportunities inherent in developing effective immersive analytics systems. The design study framework provides structured approaches for navigating the complexity of translating abstract analytical requirements into tangible immersive experiences that support meaningful data exploration activities [4]. These methodological considerations encompass user-centered design principles, iterative prototyping processes, and rigorous evaluation techniques that validate the practical utility of immersive analytics solutions across diverse application contexts. Cognitive theoretical foundations supporting spatial data representation draw extensively from research in embodied cognition, spatial reasoning, and human-computer interaction domains. These theoretical perspectives suggest that immersive analytics environments can leverage innate human spatial navigation abilities and proprioceptive feedback mechanisms to enhance analytical performance. The integration of physical movement, gestural interaction, and three-dimensional spatial reasoning creates synergistic effects that amplify analytical capabilities beyond what is achievable through traditional interface modalities.

### **3. Technical Architecture and Implementation**

The architectural foundations of immersive analytics systems rely heavily on standardized web technologies that bridge the gap between browser-based applications and specialized AR/VR hardware platforms. WebXR APIs have established themselves as critical intermediary layers that abstract device-specific implementation details while providing developers with consistent programming interfaces across diverse hardware ecosystems. These standardization efforts have fundamentally transformed the development landscape by enabling cross-platform immersive experiences that can be deployed through standard web browsers without requiring platform-specific native applications or complex installation procedures. Modern WebXR implementations incorporate sophisticated rendering architectures that manage the complex computational requirements of stereoscopic display systems, spatial tracking mechanisms, and real-time input processing across heterogeneous device configurations. The technical infrastructure underlying these systems must address challenging performance constraints while maintaining smooth frame rates and responsive interactions, particularly when rendering complex three-dimensional data visualizations that demand significant computational resources. Advanced rendering pipelines implement asynchronous processing techniques and optimized memory management strategies to ensure consistent user experiences across varying hardware capabilities and performance characteristics.

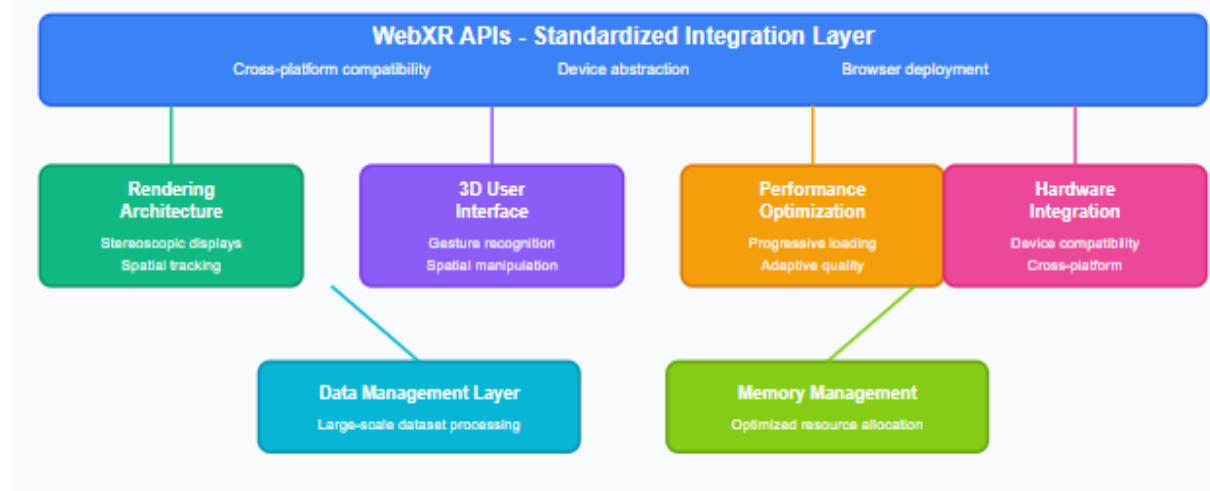


Fig 2: Technical Architecture &amp; Implementation [5,6]

Systematic analysis of immersive virtual reality applications reveals critical design patterns and architectural considerations that directly influence the effectiveness of educational and analytical implementations. Research findings demonstrate that successful immersive applications integrate multiple design elements, including spatial navigation systems, interactive manipulation interfaces, and contextual information displays that collectively enhance user engagement and learning outcomes [5]. These design elements require careful coordination between frontend rendering systems, data management architectures, and user interaction frameworks to create cohesive immersive experiences. The implementation of effective immersive analytics systems demands a comprehensive understanding of design methodologies that address both technical performance requirements and user experience considerations. Educational applications of immersive technologies have provided valuable insights into the architectural patterns that support sustained user engagement, effective information retention, and intuitive interaction workflows [5]. These lessons learned from educational implementations translate directly to analytical applications where similar cognitive processes drive user success in data exploration and insight discovery activities. Contemporary three-dimensional user interface frameworks have evolved to encompass sophisticated interaction paradigms that extend beyond traditional point-and-click metaphors to incorporate natural gesture recognition, spatial manipulation techniques, and contextual awareness capabilities. The theoretical foundations underlying these interface systems draw from extensive research in human spatial cognition, motor control, and perceptual psychology to create interaction models that align with natural human behavioral patterns [6]. These interface frameworks must balance complexity and intuitiveness while providing sufficient functionality to support demanding analytical workflows. Advanced user interface implementations for immersive environments incorporate multi-modal interaction techniques that combine visual feedback, spatial audio cues, and haptic responses to create rich sensory experiences that enhance user comprehension and task performance. The integration of multiple sensory channels requires careful architectural planning to ensure synchronized feedback

mechanisms that reinforce rather than conflict with user actions and system responses [6]. These multi-modal methods are especially crucial in analytical situations where users need to handle intricate information while keeping spatial awareness and concentrating on the task. Strategies for performance optimization in immersive analytics applications must tackle the specific computational hurdles linked to real-time 3D rendering, extensive data processing, and interactive user engagement in resource-limited browser settings. Sophisticated optimization methods incorporate progressive data loading systems, adaptive detail-level algorithms, and smart caching strategies that facilitate seamless performance on various hardware setups. These optimization approaches become critical when deploying immersive analytics solutions that must handle substantial datasets while maintaining interactive responsiveness and visual quality standards.

#### **4. Applications and Use Cases across Domains**

The systematic examination of augmented reality usability across diverse application domains reveals significant insights into the effectiveness of immersive technologies for scientific research, educational applications, and industrial implementations. Comprehensive analysis of augmented reality studies demonstrates that immersive visualization systems consistently enhance user performance in tasks requiring spatial understanding, complex data interpretation, and collaborative problem-solving activities [7]. Scientific research applications particularly benefit from augmented reality implementations that enable researchers to visualize abstract concepts through three-dimensional representations, facilitating improved comprehension of molecular structures, climate data patterns, and complex simulation results. Molecular visualization applications leverage augmented reality capabilities to transform abstract biochemical data into tangible three-dimensional models that researchers can manipulate through natural gesture interactions. These implementations enable scientists to examine protein folding patterns, drug-target binding mechanisms, and enzymatic reaction pathways within immersive environments that provide intuitive spatial context and scale relationships [7]. Climate data modeling applications utilize augmented reality frameworks to create comprehensive visualization environments where atmospheric and oceanic datasets can be explored through multi-dimensional navigation techniques that preserve temporal continuity while enabling detailed examination of regional phenomena and global interaction patterns. Complex simulation environments demonstrate enhanced analytical capabilities when integrated with augmented reality visualization systems that enable researchers to observe dynamic processes from multiple perspectives simultaneously. Scientific simulations involving fluid dynamics, electromagnetic interactions, and particle physics benefit from immersive approaches that communicate multidimensional relationships through spatially coherent representations [7]. The integration of high-performance computing environments with augmented reality visualization frameworks enables real-time exploration of simulation results, supporting immediate hypothesis validation and parameter optimization activities that accelerate scientific discovery processes.

Business intelligence applications of augmented reality technologies have demonstrated substantial improvements in analytical effectiveness, particularly for tasks involving multi-dimensional financial data exploration and market trend analysis. Augmented reality implementations enable financial analysts to examine complex market relationships through three-dimensional visualizations that reveal patterns and correlations that remain hidden within traditional dashboard interfaces [8]. Advanced augmented reality systems integrate real-time data streaming capabilities with interactive visualization frameworks, enabling dynamic exploration of market conditions, risk assessments, and performance metrics through natural navigation and manipulation techniques. The technological foundations supporting augmented reality business intelligence applications encompass sophisticated tracking systems, registration algorithms, and display technologies that enable seamless integration between virtual information overlays and physical analytical environments. These systems implement advanced computer vision techniques that maintain accurate spatial alignment between virtual data representations and physical reference points, ensuring consistent analytical experiences across diverse operational contexts [8]. Real-time data integration capabilities enable augmented reality business intelligence systems to display current market conditions, financial indicators, and performance metrics through contextually relevant visualizations that adapt to changing analytical requirements.



Fig 3: Augmented Reality Applications across Domains [7, 8]

Educational applications of augmented reality demonstrate significant potential for enhancing statistical literacy and data comprehension through interactive learning environments that transform abstract concepts into tangible experiences. Augmented reality educational systems enable students to manipulate statistical distributions, explore correlation patterns, and examine data relationships through hands-on interactions that reinforce theoretical knowledge through practical exploration activities [7]. Collaborative learning environments support simultaneous

multi-user interactions where students can share analytical discoveries and engage in peer learning activities that enhance overall educational effectiveness. Industrial design applications integrate augmented reality visualization capabilities with real-time sensor data streams to create comprehensive prototyping environments that enable engineers to assess product performance under various operational conditions. These implementations combine physical testing data with virtual design models, enabling iterative refinement processes that optimize design parameters while reducing development costs and time requirements [8]. Advanced industrial applications incorporate predictive modeling capabilities that project performance characteristics and failure modes through augmented reality visualizations, supporting proactive design optimization and risk mitigation strategies.

## 5. Evaluation and Future Directions

The comprehensive evaluation of augmented reality assembly systems reveals critical insights into the comparative effectiveness of immersive interfaces versus traditional analytical approaches across manufacturing and industrial applications. Systematic analysis demonstrates that augmented reality implementations consistently enhance task performance, reduce error rates, and improve user satisfaction when compared to conventional instruction-based assembly processes [9]. These performance improvements manifest through reduced assembly time requirements, decreased cognitive workload, and enhanced spatial understanding of complex three-dimensional relationships that are fundamental to effective analytical workflows. Manufacturing applications utilizing augmented reality technologies demonstrate significant advantages in terms of accuracy, efficiency, and knowledge transfer capabilities when compared to traditional training and analytical methodologies. Industrial implementations show measurable improvements in quality control processes, maintenance procedures, and complex assembly operations where spatial visualization plays a critical role in task completion [9]. The integration of real-time data overlays with physical environments enables workers to access contextual information, performance metrics, and analytical insights without disrupting workflow continuity or requiring attention shifts between multiple information sources. A comparative study of traditional analytical interfaces and immersive environments shows significant variations in user engagement behaviors, information retention levels, and collaborative efficiency across various industrial settings. Augmented reality systems exhibit enhanced effectiveness in situations needing concurrent access to various information feeds, intricate spatial reasoning, and immediate decision-making skills [9]. These benefits are especially evident in analytical activities that involve multidimensional datasets, as conventional screen-based interfaces create cognitive barriers that hinder successful pattern recognition and insight generation processes. Technical challenges confronting immersive analytics implementations encompass hardware limitations, software compatibility issues, and integration complexities that significantly impact deployment feasibility across enterprise environments. Hardware constraints include display resolution limitations, tracking accuracy variations, computational processing requirements, and battery life considerations that collectively

influence system usability and adoption rates [10]. Rendering performance challenges become critical when processing large-scale datasets or implementing real-time visualization updates that demand substantial graphics processing capabilities while maintaining interactive responsiveness. The use of augmented reality technologies in education encounters specific implementation hurdles concerning curriculum integration, teacher training, and the necessary technology infrastructure within institutions. A systematic review of augmented reality in education shows consistent trends of better learning results, heightened student engagement, and higher knowledge retention relative to conventional teaching methods [10]. However, successful educational implementation requires a comprehensive assessment of pedagogical consistency, technical support requirements, and accessibility considerations that foster inclusive learning opportunities for diverse student populations. Accessibility issues represent major barriers to the uptake of immersive analytics, particularly for those with disabilities, age-related challenges, or technology-related fears that may obstruct meaningful interaction with augmented reality tools. Current accessibility frameworks for immersive educational settings are less advanced than existing digital accessibility standards, resulting in challenges that hinder broad adoption [10]. Educational institutions need to tackle these accessibility issues while also handling the costs of hardware acquisition, the demands of maintenance, and the training necessities for instructors that come with implementing immersive technology. Emerging trends in artificial intelligence integration with immersive analytics systems indicate significant potential for automated pattern recognition, intelligent data interpretation, and adaptive user interface optimization within three-dimensional visualization environments. AI-assisted analytical frameworks leverage machine learning algorithms to identify statistical anomalies, recommend exploration pathways, and provide contextual guidance that enhances user analytical capabilities [9]. Collaborative immersive analytics represents another significant development trend where distributed teams can inhabit shared virtual analytical spaces, enabling synchronized data exploration activities that transcend geographical constraints and traditional collaboration limitations. Scalability challenges and organizational adoption barriers encompass technical infrastructure requirements, change management considerations, and return-on-investment evaluation complexities that influence enterprise-level immersive analytics deployment decisions. Educational adoption faces similar scalability challenges, including institutional technology policies, faculty development requirements, and student technology access disparities that constrain widespread implementation [10].

Table 1: Evaluation and Future Directions of AR Systems

Focus Area	Key Insights	Challenges
Industrial Applications	Enhanced performance, reduced errors, improved spatial understanding	Hardware limitations, integration complexity
User Engagement	Improved retention, better collaboration in immersive environments	Cognitive overload in screen-based interfaces
Educational Integration	Higher student engagement and retention	Curriculum integration, teacher training, and infrastructure gaps
Accessibility	AR fosters inclusive engagement if well-designed	Barriers for users with disabilities or tech aversion
AI & Collaboration	AI enhances pattern recognition and enables virtual teamwork	Scalability, organizational adoption hurdles

## Conclusion

The transformative possibilities of immersive analytics via AR/VR technologies fundamentally reshape human-data interaction models by constructing spatially coherent settings that utilize natural cognitive functions for improved analytical outcomes. Thorough assessment across various application fields consistently shows better results in pattern recognition, spatial awareness, and joint analytical tasks when contrasted with traditional interface methods. Advancements in WebXR technologies, frontend frameworks, and performance optimization methods have created strong architectural bases that allow for cross-platform deployment and scalable data processing abilities. Educational and industrial uses show notable benefits in knowledge exchange, task execution, and decision-making efficiency, especially for intricate multidimensional datasets that necessitate the concurrent evaluation of spatial and temporal connections. Future advancements must focus on accessibility frameworks, AI-enabled interpretation features, and cooperative immersive settings that facilitate distributed analytical tasks. Entities contemplating the adoption of immersive analytics need to tackle infrastructure demands, training necessities, and integration challenges while assessing return-on-investment factors that validate technological change projects. Ongoing progress in user-focused design methods, assessment frameworks, and accessibility norms will be crucial for achieving the complete potential of immersive analytics in various organizational settings and user groups.

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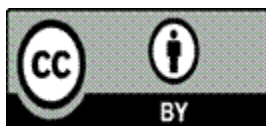
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