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Research Article

User Experience and Interaction Design Evaluation of Immersive Virtual Reality Interfaces for 3D Data Visualization in Complex Information Environments

Bentar Priyopradono [1*], Jan W. Hatulesila [2]

[1] Universitas Prof. Dr. Hazairin, SH, Indonesia bentarpriyopradono@unihaz.ac.id
[2] Universitas Patimura, Indonesia
* Corresponding Author : Bentar Priyopradono

Abstract: The increasing volume and complexity of data have made traditional 2D visualization methods insufficient for effectively exploring and understanding high-dimensional datasets. Immersive Virtual Reality (VR) presents a promising solution by providing an interactive 3D environment that enhances spatial understanding, task efficiency, and user satisfaction. This research aims to evaluate the user experience (UX) and interaction design quality of immersive VR interfaces for 3D data visualization in complex environments. The study employs a mixed-methods approach, combining usability testing, UX questionnaires, and task-based performance analysis. Participants interacted with VR prototypes designed to visualize complex data and were assessed on their ability to manipulate and explore the data efficiently. The findings show that immersive VR interfaces significantly improve spatial comprehension, reduce cognitive load, and increase task performance efficiency compared to traditional 2D systems. Additionally, user satisfaction was notably high, with participants appreciating the intuitive and engaging interaction methods. The study concludes that immersive VR can provide substantial benefits in real-world data visualization applications, particularly in domains requiring the exploration of complex and high-dimensional data. However, further research is needed to optimize VR interfaces and address challenges such as motion sickness and interaction complexity.

Keywords: Immersive Virtual Reality; 3D Data Visualization; User Experience; Spatial Understanding; Task Efficiency; Data Exploration; Interaction Design.

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1. Introduction

The exponential growth in data volume and complexity presents significant challenges for traditional 2D data visualization methods. As data becomes increasingly high-dimensional and intricate, conventional visualization techniques often struggle to effectively depict complex structures and patterns. Traditional 2D visualizations, which are primarily designed for simpler, two-dimensional data, frequently fail to convey essential information due to limitations in spatial sensitivity, interactivity, and the ability to visualize complex 3D data structures [1]. Moreover, as data sets grow in size, traditional 2D methods encounter issues such as data overlap and the loss of crucial details, making it difficult for users to discern meaningful insights [2]. These shortcomings highlight the need for more advanced approaches to data visualization that can accommodate the increasing complexity of modern data.

Immersive Virtual Reality (VR) offers a promising solution to these challenges. Unlike traditional 2D visualization techniques, VR allows users to interact with data in a three-dimensional environment, providing a more intuitive and immersive experience that enhances data interpretation and pattern recognition [3]. By leveraging VR's spatial capabilities, users can explore complex datasets more effectively, facilitating a deeper understanding of multidimensional data. Furthermore, VR environments offer increased flexibility in interaction, such as real-time data manipulation, which is particularly beneficial for analyzing dynamic and high-dimensional data [4]. The ability to manipulate and explore data in real-time within a 3D space also reduces cognitive workload and improves task performance [5]. As such, immersive VR represents a major step forward in the field of data visualization, providing a richer, more interactive approach to understanding complex data.

The primary objective of this research is to evaluate the user experience (UX) and interaction design quality of immersive VR interfaces for 3D data visualization in complex environments. This study aims to assess various interaction techniques, such as menu-based and gesture-based interactions, to determine their effectiveness in facilitating efficient and natural user interactions [6]. Previous research has shown that immersive VR environments can significantly enhance user engagement and satisfaction, especially when the interaction design is intuitive and aligned with users' mental models [7], [8]. By exploring the challenges and opportunities in designing VR interfaces, this study seeks to contribute to the development of best practices and design principles for immersive data visualization tools [9]. Through these efforts, the research aims to advance the design of VR interfaces for 3D data visualization, ensuring that they are both effective and engaging for users.

2. Literature Review

Examination of Prior Research on Data Visualization Methods and Their Limitations in Traditional 2D Environments

Traditional 2D data visualization methods have long been utilized to represent data in visual formats such as charts, graphs, and maps. However, these methods face significant limitations when it comes to handling complex, high-dimensional datasets. As data becomes increasingly high-dimensional and intricate, traditional 2D visualizations struggle to capture the underlying patterns and structures inherent in such data. These methods often fail to convey crucial information, especially when visualizing datasets that require the representation of multiple variables or spatial relationships. The limited interaction capabilities of 2D visualizations, which generally offer static, non-interactive representations, exacerbate these challenges [2]. Furthermore, the inability to integrate spatial and depth cues in 2D environments restricts users' ability to perform detailed spatial analysis, which is critical in fields such as geography, materials science, and complex system modeling [1].

Overview of Immersive VR Technologies and Their Application in Enhancing Data Comprehension and Visualization

Immersive virtual reality (VR) technologies offer a substantial improvement over traditional 2D methods, particularly in the context of visualizing complex data. VR allows users to immerse themselves in a three-dimensional environment, enhancing data interpretation by providing spatial engagement and sensory immersion [10]. This spatial capability enables users to manipulate and explore data within a virtual space, leading to improved comprehension and interaction with high-dimensional datasets [11]. For example, systems utilizing VR platforms such as the HTC Vive and Oculus have demonstrated significant improvements in the accuracy of data interpretation, as well as reductions in cognitive workload compared to traditional 2D interfaces [12], [13]. Moreover, immersive analytics (IA) has been shown to foster innovation in data analysis by facilitating more intuitive, real-time exploration of data, allowing users to interact with data dynamically [14]. These advancements highlight VR's potential to revolutionize how users engage with and comprehend complex datasets.

Review of User Experience Frameworks Relevant to VR Interfaces

User experience (UX) in VR environments is a crucial factor in determining the effectiveness and usability of immersive data visualization tools. Several UX frameworks have been developed to assess the various dimensions of user interaction with VR systems, including usability testing, cognitive load, and spatial understanding. Effective UX design in VR systems involves creating clear, minimalistic user interfaces that reduce user confusion and facilitate intuitive interactions. Multimodal feedback, including visual, auditory, and haptic cues, plays a significant role in enhancing the user experience by providing users with sensory feedback during interactions [15]. Cognitive load is also a critical consideration, as VR environments can sometimes increase perceived task difficulty, particularly in complex data exploration scenarios [16]. Tools like the Multidimensional Virtual Reality User Experience Questionnaire (MuVRUX) have been specifically designed to measure UX across several factors, including presence, immersion, emotional engagement, and usability, allowing for a comprehensive evaluation of the VR interface [15]. Additionally, frameworks such as the Semiotic Framework for VR usability provide valuable insights into the symbolic and communicative aspects of VR interfaces, offering theoretical models that can guide UX improvement efforts [17].

User Experience in Digital Information Systems

The rapid development of digital information environments has increased the complexity of how users interact with data, systems, and technologies. In such environments, user experience (UX) becomes a critical factor determining the effectiveness and acceptance of digital platforms. User experience refers to the overall perception and response of users resulting from the use of a system, including aspects such as usability, accessibility, satisfaction, and engagement. As digital systems evolve into more complex and interactive platforms, UX design must consider not only functionality but also cognitive load, interaction flow, and emotional responses during system usage.

Danang et al., (2025) emphasize that digital transformation initiatives require user-centered technological environments that support digital literacy and sustainable engagement. Their work highlights the importance of designing systems that empower users to interact effectively with digital services, particularly within complex governance infrastructures. Similarly, Danang, Dianta, et al., (2025) argue that the integration of advanced technologies such as artificial intelligence and blockchain must be accompanied by user-oriented design principles to ensure long-term adoption and cultural acceptance of digital systems. These perspectives reinforce the importance of evaluating user experience in advanced technological interfaces, including immersive virtual reality environments designed for complex data visualization.

Interaction Design in Immersive Digital Environments

Interaction design focuses on how users communicate with digital systems through interfaces, controls, feedback mechanisms, and navigational structures. In immersive environments, interaction design becomes significantly more complex because users interact with spatial objects, virtual environments, and multidimensional data simultaneously. Unlike traditional graphical user interfaces, immersive interfaces require users to navigate and manipulate information within a three-dimensional space, which introduces new challenges related to usability, spatial orientation, and cognitive processing.

Putranti et al., (2024) demonstrate that interactive digital environments can significantly increase user engagement when systems are designed with participatory interaction elements. Their research on work gamification indicates that user engagement increases when systems allow active involvement, intuitive interaction, and meaningful feedback mechanisms. These principles are particularly relevant to immersive virtual environments where users must maintain sustained attention while navigating complex information spaces. Furthermore, Englishtina Englishtina, H. R. D. Putranti et al., (2025) show that combining interactive technologies with contextual narratives enhances learning experiences and user understanding. This finding suggests that immersive systems should incorporate meaningful interaction patterns that support user comprehension and exploration within complex digital environments.

Immersive Virtual Reality Interfaces

Immersive Virtual Reality (VR) represents an advanced interface paradigm that allows users to experience and interact with digital environments as if they were physically present within them. Through the use of head-mounted displays, motion tracking, and spatial interaction tools, immersive VR enables users to explore digital objects and environments in three-dimensional space. This capability makes VR particularly suitable for applications that require spatial understanding, such as complex data visualization, simulation, training systems, and scientific exploration.

The design of immersive VR systems must consider both technical performance and human interaction factors to ensure an effective user experience. In complex computational environments, adaptive frameworks are often required to maintain system responsiveness and stability. Danang, Wahyono, et al., (2025) propose adaptive frameworks integrating machine learning, blockchain, and trusted execution environments to support dynamic and secure digital infrastructures. Although their work focuses on cloud security architectures, the concept of adaptive system design is highly relevant for immersive VR systems, which must dynamically process large volumes of data while maintaining smooth interaction and real-time responsiveness. Such adaptive architectures ensure that immersive environments remain stable, interactive, and responsive during intensive data visualization processes.

3D Data Visualization in Complex Information Environments

Modern information environments often involve large-scale datasets characterized by multidimensional relationships, dynamic updates, and high computational complexity. Traditional two dimensional visualization methods frequently struggle to represent such datasets effectively. Three-dimensional visualization techniques provide additional spatial dimensions that enable users to identify patterns, correlations, and structures within complex data more intuitively.

However, effective 3D visualization requires reliable computational infrastructure capable of processing data streams efficiently. Danang, Siswanto, et al., (2025) demonstrate that distributed environments require intelligent processing approaches to handle real-time data analysis effectively. Similarly, Danang, Santoso, et al., (2025) highlight the importance of real-time detection and response mechanisms in cloud-edge infrastructures to maintain system performance under heavy data processing loads. These findings suggest that immersive 3D visualization systems must be supported by robust computational frameworks capable of processing large datasets while maintaining low latency and interactive responsiveness.

Security and Reliability in Complex Digital Systems

In complex digital environments, security and reliability play an important role in shaping user trust and system acceptance. Immersive systems designed for data visualization often operate within sensitive environments such as research laboratories, industrial monitoring systems, or decision-support platforms. As a result, system reliability and protection against cyber threats become critical components of the overall user experience.

Umam et al., (2024) propose a hybrid zero trust container-based architecture designed to ensure service continuity in cloud environments facing intelligent distributed denial-of-service attacks. Their research emphasizes that resilient system architectures are necessary to maintain service stability and prevent disruptions in digital infrastructures. Furthermore, Danang, Santoso, et al., (2025) highlight the importance of blockchain-based security mechanisms for protecting server environments from malware and ransomware threats. These studies demonstrate that system security is not only a technical requirement but also a fundamental factor influencing user confidence and trust in digital platforms.

Integration of Intelligent Systems in Modern Digital Environments

The development of modern digital systems increasingly involves the integration of intelligent technologies such as artificial intelligence, Internet of Things (IoT), distributed computing, and adaptive security architectures. These technologies enable systems to process large amounts of data, automate complex processes, and provide real-time insights for decision-making.

Muhadi et al., (2024) demonstrate how IoT-based security systems can enhance monitoring and access control within digital infrastructures. Similarly, Umam et al., (2024) show how automation systems based on microcontrollers can improve efficiency and accuracy in monitoring physical processes. In addition, Danang, Siswanto, et al., (2025) illustrate the application of IoT technologies in monitoring environmental data such as urban water quality. These studies indicate that the integration of intelligent systems is essential for supporting advanced digital platforms. Within the context of immersive VR-based data visualization, such integration allows systems to process real-time data streams, maintain system stability, and support interactive exploration of complex information environments.

3. Proposed Method

This study evaluates the user experience (UX) and interaction design of immersive VR interfaces for 3D data visualization. A sample of 30 participants with varying levels of experience in data visualization will be selected. The evaluation combines usability testing, UX questionnaires, and task-based performance analysis to assess interaction techniques, task efficiency, and user satisfaction. Participants will interact with VR prototypes designed for high-dimensional data visualization using HTC Vive and Oculus Rift systems, which support both hand gestures and controller-based inputs. The study aims to determine how immersive VR interfaces enhance data comprehension, improve task performance, and offer a more intuitive and engaging alternative to traditional 2D methods.

Figure 1. Flowchart structure.

The deep Participants

This study will involve a sample of 30 participants, recruited from a pool of individuals with a background in data visualization, including both professionals and students from related fields such as computer science, engineering, and design. The participants will range in age from 18 to 40, ensuring a diverse set of experiences with technology and varying levels of expertise in interacting with 2D and 3D data visualizations. Participants will be selected to include a balance of genders and technical proficiency, with some having prior experience using VR interfaces for data visualization, and others being novice users. This diversity in participant characteristics will help assess the usability of immersive VR interfaces across different levels of user experience and technical skill.

Evaluation Design

The evaluation will follow a mixed-methods approach, integrating qualitative and quantitative research methods to comprehensively assess the user experience (UX) and interaction design quality of the immersive VR interfaces used for 3D data visualization. The evaluation will consist of the following components:

a) Usability Testing
A task-based assessment will be conducted where participants interact with immersive VR prototypes. The tasks will include data manipulation and analysis using 3D visualizations, designed to assess how effectively participants can use the VR interface to explore and understand complex datasets. These tasks will simulate real-world scenarios where users need to extract insights from large-scale data visualizations, assessing their ability to perform tasks efficiently and with minimal errors. The usability testing will also examine how users interact with the VR interface, focusing on their ability to navigate the virtual space and use different interaction techniques such as gesture-based and menu-based controls.

b) UX Questionnaires
After completing the usability testing, participants will fill out a UX questionnaire to evaluate their satisfaction with the VR interface. The questionnaire will include questions related to various aspects of UX, such as ease of use, satisfaction with interaction techniques, and perceived effectiveness of the immersive experience in enhancing their understanding of the data. This questionnaire will measure dimensions like presence, immersion, and cognitive load. Participants will also provide feedback on any challenges or difficulties encountered during their interactions with the VR interface.

c) Task-Based Performance Analysis
This component will focus on measuring the efficiency of participants in performing data visualization tasks within the VR environment. Metrics such as task completion time, accuracy, and error rate will be recorded. This data will provide objective insights into how well the immersive VR interface supports users in achieving their goals, comparing performance against traditional 2D data visualization methods. Performance metrics will be analyzed to determine whether VR interfaces lead to faster and more accurate completion of tasks.

Immersive VR Prototypes

The immersive VR prototypes used in this study will consist of virtual reality interfaces designed specifically for 3D data visualization. These interfaces will incorporate state-of-the-art VR technologies, such as HTC Vive and Oculus Rift, which allow for full-body motion tracking and provide a highly immersive experience. The VR prototypes will support interaction through both hand gestures and controller-based inputs, allowing participants to manipulate data visualizations in a 3D space. The data visualizations used in the prototypes will represent high-dimensional datasets, including complex multidimensional data, designed to test users' ability to comprehend and interact with intricate data structures.

The design of the VR interfaces will prioritize usability, ensuring that participants can easily navigate the virtual environment and interact with the data. Key design elements will include clear spatial arrangements of data points, intuitive control schemes for manipulating the data, and minimalistic visual interfaces to reduce cognitive overload. This will allow participants to focus on the data and its relationships, rather than being distracted by complex navigation or interface issues. The immersive nature of the VR environment will also provide spatial cues, allowing users to interact with data more naturally, as opposed to the static, flat representations of traditional 2D methods. These prototypes aim to enhance the user's understanding and manipulation of 3D data visualizations, thus addressing the limitations of traditional 2D systems.

4. Results and Discussion

The study found that immersive VR interfaces significantly enhanced users' spatial understanding and task efficiency in visualizing complex, multidimensional data. Participants were able to comprehend data structures more intuitively and interact with the data more effectively in a 3D environment, resulting in faster task completion and fewer errors compared to traditional 2D systems. While users expressed high satisfaction with the immersive experience, some challenges, such as motion sickness and difficulty with certain interaction techniques, were noted. These findings support the potential of VR to improve data comprehension and task performance, but highlight the need for further optimization of user interfaces to address usability issues and ensure a more comfortable experience.

Results

The immersive VR interfaces significantly improved users' ability to comprehend multidimensional data in space. Participants demonstrated a heightened spatial understanding of complex datasets when interacting with the VR system. The ability to manipulate data points in a 3D environment allowed users to view data relationships from multiple perspectives, enhancing their ability to discern patterns and correlations. This feature was especially useful in visualizing intricate datasets that were challenging to interpret using traditional 2D visualization methods. Participants reported that the immersive experience enabled them to interact with data in a more natural and intuitive way, contributing to a better understanding of the data's structure and dynamics.

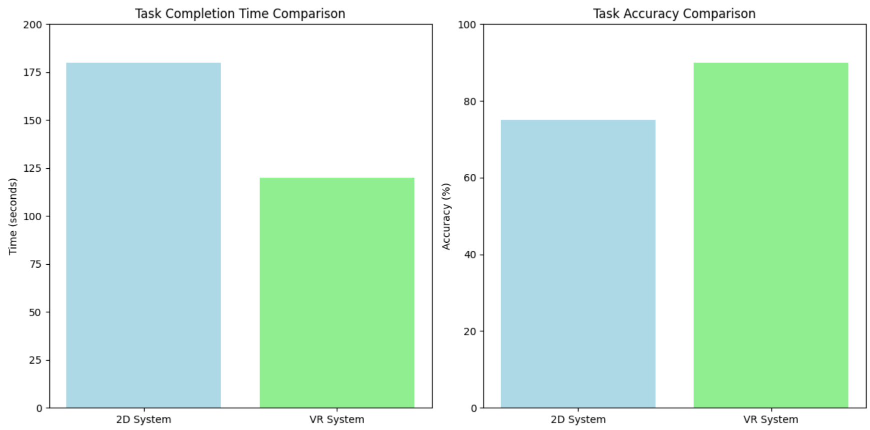

Figure 2. Task Accuracy Comparison.

The results of the study, illustrated in the supporting graphs, demonstrate the significant advantages of the VR system over the traditional 2D system in both task completion time and accuracy. Participants completed tasks much faster using the VR system (120 seconds) compared to the 2D system (180 seconds), highlighting the enhanced efficiency provided by the immersive VR interface. Furthermore, the VR system resulted in a higher percentage of correct tasks completed (90%) compared to the 2D system (75%), indicating that the immersive experience not only improved speed but also task accuracy. These findings underscore the effectiveness of immersive VR in optimizing both performance and accuracy in data visualization tasks.

In terms of task performance, participants exhibited higher efficiency when using the VR interface compared to traditional 2D systems. Tasks that required users to explore large datasets or identify complex relationships were completed faster with the VR interface. Additionally, users made fewer errors and were able to complete tasks more accurately, suggesting that the immersive nature of VR contributed to a more effective data manipulation experience. The ability to interact with the data in a 3D space, including zooming, rotating, and selecting data points, facilitated quicker and more precise task completion. The improved performance reflects the advantages of immersive VR environments in enhancing task efficiency and reducing cognitive load.

Discussion

The findings from this study align with and support existing literature on the effectiveness of immersive VR for data visualization. Previous research has consistently shown that VR enhances spatial understanding by enabling users to engage with data in a three-dimensional environment. The results of this study reinforce the idea that VR's spatial capabilities provide users with a deeper understanding of complex datasets, as they can interact with the data in a way that traditional 2D visualizations cannot offer. The ability to manipulate and view data from various angles is crucial for tasks involving high-dimensional data, as it helps users make sense of intricate patterns and structures that may not be immediately apparent in flat, 2D representations.

In addition to spatial understanding, the improvement in task efficiency observed in this study is consistent with prior research on immersive analytics. VR systems have been shown to facilitate faster and more accurate task completion by providing more interactive and intuitive interfaces. By reducing the time needed to navigate and manipulate data, VR systems enable users to focus on analyzing the data itself, rather than spending time on navigating static, two-dimensional visualizations. These findings suggest that immersive VR not only enhances the understanding of data but also improves the overall efficiency of data exploration and analysis.

However, despite the positive outcomes, some challenges remain. A few participants reported issues with motion sickness or discomfort when interacting with the VR system for extended periods, highlighting the importance of refining the user interface and controls to ensure a more comfortable experience. Additionally, while the VR interface improved task performance, some users struggled with complex interaction techniques, especially when using gesture-based controls for precise data manipulation. This indicates that further optimization of the interface and controls is necessary to enhance usability, particularly for users who are less familiar with VR technology. Future research should focus on addressing these usability issues to improve the overall user experience and maximize the potential of immersive VR for data visualization.

5. Comparison

The comparison between immersive VR interfaces and traditional 2D desktop-based data visualization methods highlights several key advantages of VR in terms of cognitive benefits. First, immersive VR interfaces significantly enhance spatial awareness, which is a critical aspect when dealing with complex, high-dimensional data. Unlike 2D desktop interfaces, which limit users to a flat, static view of the data, VR allows for dynamic interaction with data in a three-dimensional space. This spatial flexibility enables users to explore data relationships more intuitively by adjusting their viewpoint, zooming, and rotating data points, which is particularly helpful for identifying intricate patterns or correlations. The ability to immerse oneself in the data space reduces cognitive overload and improves the user's understanding of complex datasets. Additionally, VR interfaces often support multitasking more effectively, as users can manipulate multiple data points simultaneously, whereas 2D systems are limited by the flat screen space and lack of depth perception, making multitasking more cumbersome. This combination of enhanced spatial awareness and multitasking ability provides significant cognitive benefits, especially in tasks that require the understanding of complex and multidimensional data.

When comparing immersive VR systems with non-immersive 3D visualization systems, several differences emerge in terms of interaction flexibility and user engagement. Non-immersive 3D interfaces, while offering a 3D representation of data, often rely on traditional input devices such as a mouse or keyboard, limiting the user's ability to interact naturally with the data. In contrast, immersive VR systems provide a more intuitive and flexible interaction model, where users can engage with the data using hand gestures, body movements, or specialized controllers. This level of interaction allows users to explore the data in a more natural and immersive way, resulting in higher engagement and a deeper understanding of the data. Furthermore, the immersive nature of VR makes the experience more engaging, as users feel more involved in the data exploration process compared to the passive engagement in non-immersive 3D environments. VR interfaces also provide real-time feedback and support for continuous, dynamic manipulation of the data, whereas non-immersive systems often present more static representations that require users to perform additional steps or input commands to modify the view. Overall, immersive VR systems offer a more flexible, intuitive, and engaging experience compared to non-immersive 3D interfaces, particularly when dealing with complex and multidimensional data.

6. Conclusions

The findings of this study demonstrate that immersive VR interfaces provide substantial improvements in spatial understanding, task efficiency, and user satisfaction in complex data visualization environments. Participants showed a significant enhancement in their ability to comprehend multidimensional data, aided by the immersive, interactive nature of the VR system. The ability to manipulate data in a 3D space allowed users to uncover complex patterns and relationships that would have been difficult to interpret using traditional 2D methods. Additionally, participants completed tasks faster and with greater accuracy, highlighting the efficiency of VR interfaces in real-time data exploration. User satisfaction was notably high, with participants appreciating the immersive experience and intuitive interaction methods offered by the VR system.

The practical implications of these findings suggest that immersive VR could be highly beneficial in real-world data visualization applications, particularly in fields that require the analysis of complex, high-dimensional datasets, such as scientific research, engineering, and finance. By enabling users to interact with data in an intuitive and dynamic 3D space, immersive VR can enhance decision-making processes and improve the accuracy and efficiency of data analysis. Its ability to provide an engaging and interactive environment also supports deeper user engagement, which is crucial for effective data comprehension and analysis.

Future research should focus on addressing the usability challenges identified in this study, such as optimizing interaction techniques and minimizing issues related to motion sickness. Improvements in VR interface design are necessary to ensure that these systems are accessible and comfortable for a wider range of users, particularly those who are new to VR technology. Further exploration into the application of immersive VR in different data domains will also help to refine the tools and methods needed to fully exploit the potential of VR in data visualization.

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