Research Trends in Human-Computer Interaction for Immersive Virtual Reality Applications: A Bibliometric Study (2010-2026)

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Abstract*—The rapid advancement of immersive technologies has significantly expanded the scope of Human-Computer Interaction (HCI) within the context of Immersive Virtual Reality (IVR). Despite the growing body of research, the field remains fragmented, with limited understanding of its intellectual and thematic development. This study conducts a comprehensive bibliometric analysis of HCI research within IVR using data retrieved from the Web of Science (WoS) Core Collection. A total of 1,185 publications from 2010 to 2026 were initially identified and refined to 1,129 records following a systematic screening process. The analysis employs co-citation and keyword co-occurrence techniques using VOSviewer to examine both the knowledge base and thematic development of the field. The findings reveal a substantial increase in publication output and citation impact, indicating the growing maturity and relevance of HCI research in IVR. Co-citation analysis identifies four major intellectual domains: presence and immersive experience, user experience and application contexts, usability and human factors, and behavioral and psychological interaction. Meanwhile, keyword co-occurrence analysis uncovers four dominant thematic clusters, including core interaction and system design, human-centered computing, visualization and spatial interaction, and emerging immersive technologies. This study contributes by providing a structured and data-driven mapping of the research landscape, emphasizing the relationships between interaction design, user experience, and technological advancement. The findings offer both theoretical and practical implications for advancing more integrated and user-centered approaches in immersive virtual environments, while also identifying key directions for future research.

***Keywords*—Human-computer interaction (HCI); Immersive virtual reality (IVR); immersive technologies; User experience (UX); bibliometric analysis; science mapping**

I. Introduction

Human-Computer Interaction (HCI) has become a fundamental domain in understanding how users engage with interactive systems as digital technologies move toward more immersive and experiential forms. The emergence of Immersive Virtual Reality (IVR) has significantly expanded the boundaries of HCI by introducing fully interactive environments that enable users to engage through natural, spatial, and embodied interaction [1]. Unlike traditional interfaces, IVR systems rely on advanced technologies such as head-mounted displays (HMDs), motion tracking, and multimodal feedback, thereby redefining how interaction is designed and evaluated within digital environments [2][3]. Within this context, core HCI constructs such as user experience (UX), usability, interaction design, and navigation have become increasingly critical in determining the effectiveness of IVR systems. User experience in immersive environments extends beyond functional performance to encompass factors such as presence, engagement, and perceived realism, all of which influence how users interpret and respond to virtual stimuli [3]. Similarly, usability in IVR is not limited to efficiency and effectiveness but also involves considerations of physical comfort, cognitive load, and ease of interaction within three-dimensional spaces [4]. Interaction design in IVR further requires the development of intuitive techniques such as gesture-based input, gaze interaction, and haptic feedback, which align with human perceptual and motor capabilities [5]. In addition, navigation within virtual environments plays a pivotal role in shaping user experience, as users must be able to orient themselves, move seamlessly, and interact with virtual objects without confusion or disorientation [6].

The shift toward immersive interaction has introduced new opportunities as well as challenges for HCI research. While IVR enables more natural and engaging forms of interaction, it also raises critical issues such as cybersickness, cognitive overload, and user disorientation, which can negatively affect user performance and overall experience [7], [8], [9]. These challenges underscore the need for robust HCI design strategies that integrate usability, interaction efficiency, and user-centered evaluation to ensure effective immersive experiences [10]. However, this growing body of literature is often fragmented across multiple research streams, making it difficult to obtain a comprehensive understanding of the field's development and key contributions. Traditional review approaches may provide valuable insights into specific areas but are limited in their ability to systematically map the overall structure and evolution of research within this domain [11]. In this context, bibliometric analysis offers a systematic and quantitative approach to examining large volumes of scientific literature. By analyzing relationships between publications and keywords, bibliometric methods enable the identification of influential studies, research trends, and thematic developments within a field [12], [13]. Such an approach is valuable for HCI research in IVR, where the interdisciplinary nature of the field contributes to its complexity and rapid evolution.

Therefore, this study aims to conduct a bibliometric analysis of research trends in Human-Computer Interaction within Immersive Virtual Reality applications. Specifically, this study focuses on two key analytical techniques:

- Co-citation analysis is employed to uncover the structure of the field by identifying relationships among influential publications and revealing foundational research streams.
- Keyword co-occurrence analysis is conducted to explore the dominant and emerging research themes that are interconnected within the literature.

II. Literature Review

Human-Computer Interaction (HCI) has evolved into a multidisciplinary field that examines how users interact with digital systems through the integration of design, cognition, and technology [14]. Within this domain, increasing attention has been directed toward Immersive Virtual Reality (IVR), which has successfully introduced different interaction paradigms compared to conventional systems [15]. In IVR, users are not merely interacting with interfaces but are actively situated within virtual environments, requiring continuous perception, movement, and real-time feedback [16]. In this context, HCI becomes critically important as it serves as the foundation for designing intuitive, efficient, and user-centered interactions that directly influence how users perceive and engage with immersive systems. Poorly designed interaction mechanisms can disrupt immersion, reduce usability, and negatively impact user performance, while effective HCI design enhances presence, engagement, and overall system effectiveness [1]. As such, HCI is not only a supporting component but a central determinant of the success and acceptance of IVR applications across various domains [4]. For example, as users are fully immersed within virtual environments, the design of interaction mechanisms directly influences their ability to perceive, navigate, and engage with digital content [17]. Ineffective interaction design may lead to confusion, reduced immersion, and poor task performance, while well-designed HCI enhances presence, engagement, and user satisfaction [4]. Therefore, HCI is not merely a supporting component but a central factor that governs the success, acceptance, and overall user experience of IVR applications across various domains [18].

On the other hand, a central aspect of HCI research in IVR lies in the examination of user experience, which encompasses usability, interaction design, and navigation as key determinants of system effectiveness. Usability in immersive environments goes beyond efficiency and effectiveness, encompassing ease of interaction, physical comfort, and the management of cognitive load, while interaction design emphasizes the development of intuitive techniques such as gesture-based input, gaze interaction, and haptic feedback that align with human perceptual and motor capabilities [19]. On the other hand, navigation plays a pivotal role in enabling users to orient themselves and move seamlessly within three-dimensional spaces, directly influencing spatial awareness and task performance [20]. Despite extensive research efforts, these elements are often investigated independently, leading to fragmented insights and limited integration across usability, interaction, and navigation perspectives. Furthermore, inconsistencies in evaluation methods have resulted in a lack of standardized frameworks for assessing user experience in IVR [21]. Human factors such as cybersickness and cognitive load further complicate this landscape, as they significantly impact user comfort and performance [22]. From a theoretical perspective, several frameworks have been employed to explain user interaction and experience in immersive environments. The Cognitive Theory of Multimedia Learning (CTML) proposed by Mayer provides insights into how users process information in IVR, especially in relation to cognitive load and instructional effectiveness [23], [24]. Presence theory further explains the psychological state of “being there,” emphasizing the importance of interaction fidelity and sensory consistency in enhancing immersion [25].

Additionally, the concept of embodied cognition highlights the role of physical interaction and bodily movement in shaping user understanding and engagement within virtual environments [26]. While these theories offer valuable perspectives, their application in HCI research for IVR remains fragmented, with limited integration into practical interaction design and evaluation approaches.

Despite the growing body of literature, research in HCI and IVR remains highly fragmented across multiple domains and research streams. Existing studies often focus on isolated aspects such as interaction techniques, usability, or human factors, without establishing clear relationships between these components [27]. Moreover, current review approaches are often limited in scope or rely on qualitative synthesis, which may not fully capture the structural relationships between studies or the evolution of research themes over time [28]. This limitation restricts the ability to identify dominant research clusters, influential works, and emerging directions within the field [29]. Therefore, there is a need for a systematic and data-driven approach to synthesize the expanding body of literature and provide a comprehensive understanding of the field. In response to this gap, this study employs a bibliometric approach integrating co-citation and keyword co-occurrence analyses to map both the intellectual structure and thematic development of HCI research within IVR.

III. Methodology

A. Bibliometric Approach

Bibliometric analysis has emerged as a rigorous and systematic approach for examining the structure and development of scientific research within a given domain [30]. Unlike traditional narrative reviews, which are often limited by subjective interpretation, bibliometric methods employ quantitative techniques to analyze large volumes of scholarly data, enabling the identification of publication patterns, influential works, and knowledge structures [12]. This approach is appropriate in rapidly evolving and interdisciplinary fields such as Human-Computer Interaction (HCI) and Immersive Virtual Reality (IVR). Among the various bibliometric techniques, co-citation analysis and keyword co-occurrence analysis are widely recognized for their complementary strengths in uncovering both the intellectual and thematic dimensions of a research field [31]. For this study, the co-citation analysis and keyword co-occurrence analysis have been selected to meet the two objectives of the study:

- Co-citation analysis examines the frequency with which two documents are cited together by subsequent publications, thereby revealing the underlying intellectual structure and identifying seminal works that have significantly influenced the development of the domain [32]. By mapping co-citation networks, researchers can detect clusters of related studies, which often correspond to distinct research streams or theoretical foundations.
- Keyword co-occurrence analysis focuses on the relationships between frequently used terms within publications, providing insights into the conceptual and thematic structure of research. This technique assumes that keywords appearing together in multiple documents are likely to represent related concepts or research topics. As such, co-occurrence analysis enables the identification of dominant themes, emerging trends, and the evolution of research topics over time [33].

The integration of co-citation and keyword co-occurrence analyses offers a comprehensive perspective on the development of a research field by simultaneously capturing its foundational knowledge base and its evolving thematic landscape. This dual approach is relevant for HCI research in IVR, where understanding both the theoretical underpinnings and emerging interaction paradigms is essential for advancing user-centered design and improving immersive experiences.

B. Research Design and Data Collection Procedure

This study adopts a quantitative bibliometric research design to examine research trends in Human-Computer Interaction (HCI) within Immersive Virtual Reality (IVR), utilizing data retrieved from the Web of Science (WoS) Core Collection. The search was conducted using the Topic field, incorporating keywords related to "human-computer interaction" AND "immersive virtual reality" OR "virtual reality," and further refined with relevant HCI terms such as "user experience" OR "usability" OR "interaction". The search was limited to English-language articles and review papers published between 2010 and 2026. An initial 1,185 records were retrieved and exported as plain text files containing full records and cited references. A PRISMA-informed screening process involving duplicate removal, title and abstract screening, and keyword standardization was then performed, resulting in a final dataset of 1,129 publications (Fig. 1). This structured procedure improves the transparency and reproducibility of the study.

The analysis was performed using VOSviewer to visualize bibliometric networks based on similarity measures, where node proximity represents relationship strength and clusters indicate distinct research themes. In line with the study objectives, co-citation analysis was employed to identify the intellectual structure of the field, while keyword co-occurrence analysis was used to examine its thematic development.

A minimum citation threshold of 15 and a keyword occurrence threshold of 16 were applied, with both thresholds iteratively calibrated to achieve clear and meaningful network visualizations while minimizing noise.

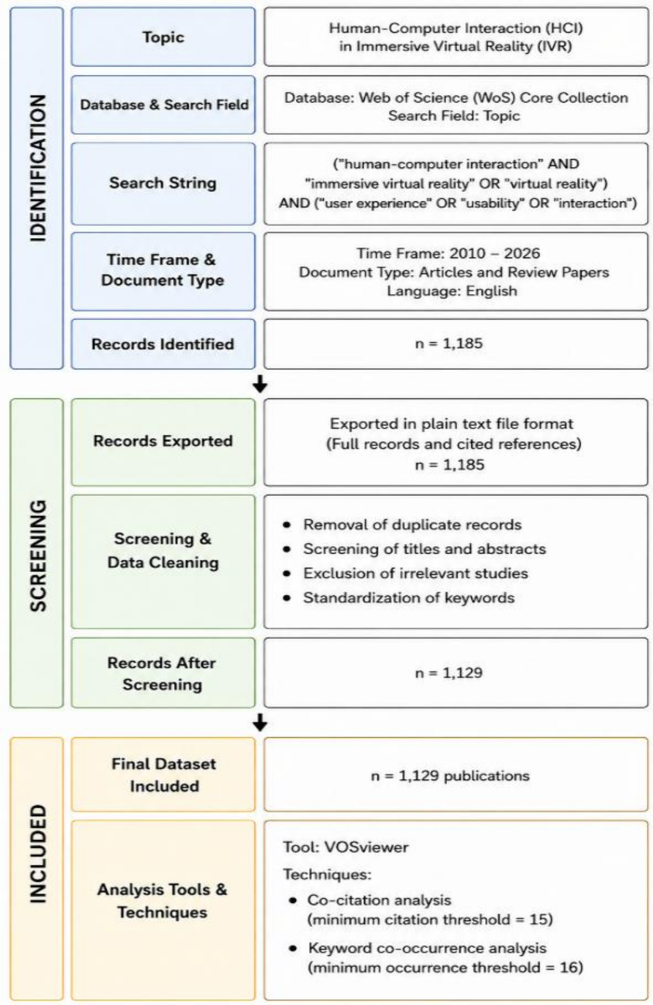

Fig. 1. Flow diagram of the screening process.

IV. RESULT

A. Trend in Publication

The Web of Science (WoS) database was searched on 28 April 2026 to retrieve relevant publications for this study. The analysis of publication trends reveals a significant and sustained growth in research related to Human-Computer Interaction (HCI) within Immersive Virtual Reality (IVR) over the examined period. A total of 1,185 publications were identified, indicating increasing scholarly interest in this domain. In the early stage (2010–2015), the number of publications remained relatively low and relatively stable, with fewer than 25 publications per year, reflecting the nascent development of IVR technologies and their limited integration within HCI research. Fig. 2 highlights the number of publications and citations received for these publications.

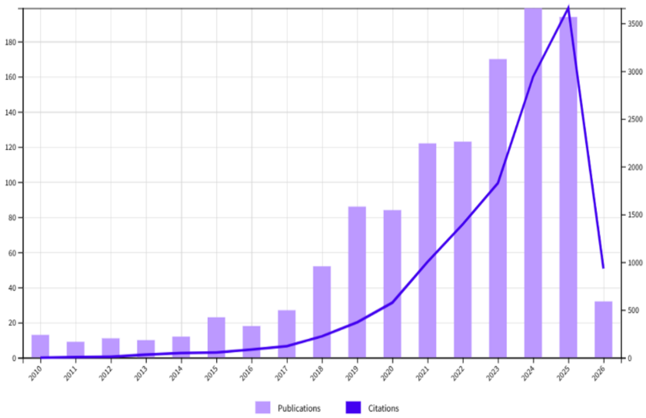

Fig. 2. Number of publications and citations between 2010 and 2026.

A noticeable upward trend emerged around 2017, followed by a rapid increase from 2018 onwards. This period represents a critical turning point, with publication output rising significantly to over 80 publications in 2019 and continuing to grow in subsequent years. The expansion became more pronounced between 2021 and 2025, when annual publications consistently exceeded 120, peaking at approximately 190 publications in 2024. This surge is likely associated with technological advancements in immersive systems, increased accessibility of VR devices, and a growing emphasis on user experience and interaction design in virtual environments. In parallel, citation trends demonstrate a similar trajectory of growth, indicating not only an increase in research output but also a strengthening academic impact.

The total number of citations reached 13,287, with an average of 11.21 citations per publication and an H-index of 53, suggesting a mature and influential research domain. The sharp rise in citations after 2020 further reflects the increasing relevance and recognition of HCI research in IVR. A decline in publication count is observed for 2026; however, this is likely due to incomplete indexing for the current year rather than an actual reduction in research activity. Overall, the findings indicate that HCI research in IVR has evolved from an emerging field into a rapidly expanding and impactful domain, demonstrating strong and sustained growth in recent years.

B. Co-Citation Analysis

Co-citation analysis was conducted to examine the structure of research in Human-Computer Interaction (HCI) within Immersive Virtual Reality (IVR). A minimum citation threshold of 15 citations was applied, resulting in 39 cited references being included in the analysis. The network visualization generated using VOSviewer revealed four distinct clusters, such as presence and immersion (theoretical foundation), user experience and applications (applied research), usability and evaluation (measurement frameworks), and behavioral and social interaction (human-centered perspective). Each of these clusters represents a major research stream within the domain. These clusters are differentiated by color and reflect the foundational knowledge areas that have shaped the development of HCI in IVR. As illustrated in Fig. 3, the network exhibits a structured knowledge domain, which is characterized by strong interrelationships among key studies.

To further examine the intellectual foundations of the field, the most influential co-cited references were identified based on their citation frequency and total link strength within the network. These highly cited works represent the core knowledge base that has significantly shaped the development of Human-Computer Interaction (HCI) research in Immersive Virtual Reality (IVR). They reflect key research domains, including presence and immersion, usability and human factors evaluation, cognitive workload, and application-oriented studies. Among these, [34] emerged as the most highly cited reference with 69 citations and a total link strength of 145, highlighting its dominant role in establishing standardized measurement of simulator sickness in immersive environments.

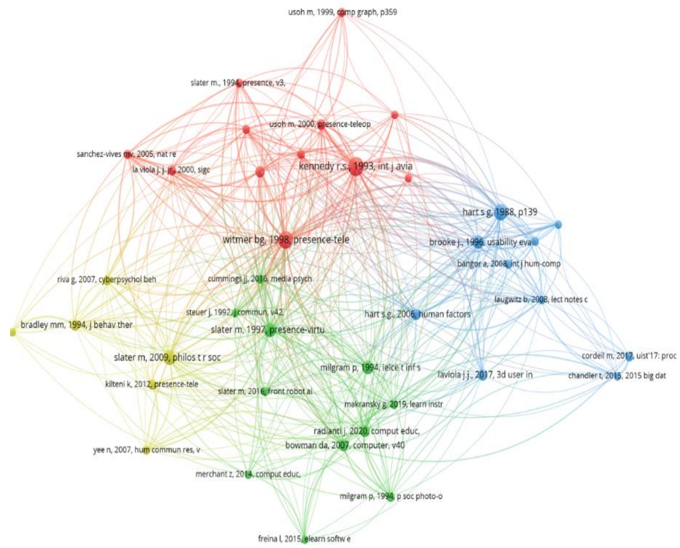

Fig. 3. Co-citation network analysis visualization.

Similarly, [35] demonstrated strong network connectivity with 61 citations and the highest total link strength of 161, indicating its central influence in presence measurement research. Other notable contributions include [36] with 53 citations (TLS = 96) and [37] with 41 citations (TLS = 131), both of which further reinforce the importance of cognitive workload and presence as key research themes. The prominence of these references indicates their critical role in establishing theoretical frameworks, measurement instruments, and interaction paradigms that underpin current research trends. Table I presents the top 10 co-cited references, highlighting their citation impact, network connectivity, and scope of study.

The predominance of earlier publications among the top co-cited references is expected, as these studies established the theoretical foundations and measurement instruments that continue to underpin HCI research in IVR. Foundational works such as [34] and [35] remain highly cited due to their enduring contributions to evaluating simulator sickness, presence, and usability. In contrast, more recent publications have had less time to accumulate citations despite their growing influence. The co-citation analysis identified four major clusters representing the intellectual structure of HCI research in IVR. Using a minimum citation threshold of 15, a total of 39 references were included. For clarity and analytical focus, each cluster is interpreted based on its most influential (top-cited) references, which best represent the core themes of the cluster.

TABLE I. TOP TEN CO-CITED REFERENCES WITH THE STRONGEST TOTAL LINK STRENGTH

Rank	Reference	Citations	Total Link Strength	Scope of Study
1	[34]	69	145	Development of the Simulator Sickness Questionnaire (SSQ).
2	[35]	61	161	Introduction of the Presence Questionnaire.
3	[36]	53	96	Proposal of the NASA-TLX model for assessing cognitive workload.
4	[37]	41	131	Theoretical exploration of presence in virtual environments.
5	[53]	42	76	Conceptual discussion on place illusion and plausibility illusion.
6	[50]	37	56	Introduction of the reality–virtuality continuum.
7	[40]	34	69	Development of the System Usability Scale (SUS).
8	[38]	30	66	Systematic review of IVR applications in higher education.
9	[39]	28	69	Comprehensive framework on 3D interaction techniques.
10	[52]	25	68	Development of presence measurement models.

Source. Author's interpretation derived from VOSviewer analysis.

Cluster 1 (Red): Presence and Immersion comprise influential studies such as [34], [35], and [37], which establish the theoretical and measurement foundations of presence, immersion, and simulator sickness in virtual environments. From an HCI perspective, this cluster is critically important as it defines the core experiential outcomes such as presence, immersion, and comfort that determine the success of interaction in IVR. These constructs directly influence user experience and usability, as poor immersion or high discomfort can negatively affect interaction performance and system acceptance. However, while these studies provide strong theoretical and measurement foundations, they offer limited insight into how specific HCI design elements (e.g., interaction techniques or navigation methods) can be optimized to enhance these outcomes, indicating a gap between theory and design implementation.

Cluster 2 (Green): User Experience and Application-Oriented Research includes key studies such as [29], [38], and [39], focusing on user experience, education, and interaction techniques in IVR. However, many studies within this cluster emphasize application outcomes (e.g., performance, learning effectiveness) rather than systematically analyzing how usability, interaction design, and navigation mechanisms contribute to these outcomes. This suggests that HCI elements are often embedded but not explicitly examined, limiting a deeper understanding of interaction design in IVR.

Cluster 3 (Blue): Usability and Human Factors Evaluation is represented by [40] and [36], which introduce widely adopted evaluation instruments such as the System Usability Scale (SUS) and NASA-TLX. This cluster plays a crucial role in HCI by providing measurement frameworks for assessing usability, workload, and user satisfaction in IVR systems. These factors are essential for understanding how users interact with immersive environments and for improving interaction efficiency and system design. However, a key limitation is that these tools were originally developed for non-immersive systems, and their direct application to IVR may not fully capture unique aspects such as spatial interaction, embodiment, and navigation complexity. This highlights the need for IVR-specific HCI evaluation frameworks that better reflect immersive interaction characteristics.

The last cluster (Cluster 4 (Yellow): Behavioral and Psychological Interaction) represented by works such as [41], [42], and [43], which explore user behavior, emotional response, and social interaction in virtual environments. These studies provide insights into how users respond cognitively and emotionally within immersive systems. In relation to HCI, this cluster is important as it informs the design of user-centered and emotionally engaging interactions in IVR. Understanding user behavior and emotional response is essential for improving interaction design, engagement, and overall user experience. However, these studies often remain at a descriptive or theoretical level, with limited translation into practical HCI design strategies, such as improving usability or navigation. This creates a gap between behavioral insights and interaction design implementation in IVR systems, as summarized in Table II.

TABLE II. SUMMARY OF CO-CITATION CLUSTERS ON HCI FOR IVR

Cluster	Cluster Label	Number of Publications	Representative Publications
Cluster 1 (Red)	Presence and Immersion in Virtual Environments	12	[34],[35],[37],[53]
Cluster 2 (Green)	User Experience and Application-Oriented Research	10	[38],[39]
Cluster 3 (Blue)	Usability and Human Factors Evaluation	9	[40],[36]
Cluster 4 (Yellow)	Behavioral and Psychological Interaction	8	[41],[42],[43]

Source. Author's interpretation derived from VOSviewer analysis

C. Co-Occurrence of Keyword Analysis

A co-occurrence analysis of keywords was conducted to identify the dominant research themes in Human-Computer Interaction (HCI) within Immersive Virtual Reality (IVR). A minimum occurrence threshold of 16 was applied, resulting in 48 out of 3,407 keywords being included in the analysis. The findings indicate that “virtual reality” (549 occurrences) is the most dominant keyword, followed by “human-computer interaction” (279 occurrences), “human-centered computing” (183 occurrences), and “human computer interaction (HCI)” (153 occurrences), highlighting the central role of immersive technologies and user-centered interaction. Additional keywords such as “interaction paradigms”, “augmented reality”, and “visualization” reflect a strong emphasis on interaction design and technological development, while terms such as “design”, “system”, and “environments” indicate the importance of system implementation. The presence of keywords related to applications, including “education” and “mixed reality”, further suggests the expanding scope of IVR research. However, variations in similar keywords and the distribution of themes indicate a degree of fragmentation, where key HCI components such as usability, interaction design, and user experience are not fully integrated. Table III presents the top 15 most frequently co-occurring keywords identified in this study. The relationships among these keywords are further illustrated through network visualization (see Fig. 4), which reveals several distinct yet interconnected thematic clusters, as discussed in the following section.

TABLE III. THE 15 MOST FREQUENT KEYWORDS IN THE KEYWORD CO-OCCURRENCE ANALYSIS

Rank	Keyword	Occurrences	Total Link Strength
1	virtual reality	549	1177
2	human-computer interaction	279	513
3	human-centered computing	183	659
4	human computer interaction	153	548
5	interaction paradigms	128	487
6	human computer interaction	95	181
7	augmented reality	88	218
8	visualization	65	177
9	virtual-reality	64	157
10	environments	50	145
11	design	49	123
12	mixed reality	47	140
13	education	46	146
14	system	38	110
15	computing methodologies	27	149

Source. Author’s interpretation derived from VOSviewer analysis

Cluster 1 (Red), consisting of 23 keywords, represents the core domain of interaction, system design, and user experience in immersive virtual reality. Prominent keywords such as “virtual reality”, “human-computer interaction”, “user experience”, “usability”, “design”, and “system” indicate a strong emphasis on the development and evaluation of interactive virtual environments. The centrality of “virtual reality” and “human-computer interaction” highlights that this cluster forms the foundational layer where immersive systems and user interaction are closely integrated [25][39]. The presence of “user experience” and “usability” reflects the importance of evaluating how users interact with virtual environments in terms of efficiency, effectiveness, and satisfaction, which are core principles in HCI [40]. In immersive contexts, these aspects are closely associated with interaction quality, system responsiveness, and task performance. Keywords such as “performance”, “behavior”, and “experience” further reinforce this focus, suggesting that user outcomes and engagement are critical indicators of system effectiveness [29]. Additionally, the inclusion of “immersion” and “environments” highlights the experiential nature of interaction in IVR, where users’ perception and engagement are influenced by the design of the virtual space [37]. Emerging terms such as “metaverse” and “machine learning” indicate a shift toward more advanced and adaptive immersive systems. However, despite the strong presence of these keywords, the cluster suggests that usability, interaction, and performance are often examined independently, indicating a lack of integrated approaches in designing cohesive user experiences within immersive virtual environments.

Cluster 2 (Green), consisting of 11 keywords, focuses on human-centered computing and interaction paradigms, with key terms such as “human-centered computing”, “interaction paradigms”, “user studies”, “HCI design and evaluation methods”, and “computer graphics”. These keywords highlight the importance of designing interactive systems that align with human capabilities and user needs [44] [46]. The presence of “interaction paradigms” reflects ongoing exploration of novel interaction techniques in immersive environments [39]. Keywords such as “user studies” and “empirical studies in HCI” indicate the reliance on experimental and user-based evaluation methods to assess system effectiveness [45]. Meanwhile, “computer graphics” and “graphics systems and interfaces” support the visual and interactive components essential for immersive experiences. The inclusion of “mixed reality” and “applied computing” further suggests the extension of interaction paradigms beyond VR into broader immersive ecosystems. However, while this cluster emphasizes methodologies and conceptual frameworks, it provides limited insight into how these approaches are translated into practical interaction design solutions in immersive environments.

Cluster 3 (Blue), consisting of 10 keywords, represents research on visualization, perception, and spatial interaction in immersive environments. Key terms such as “visualization”, “virtual environments”, “perception”, “navigation”, and “three-dimensional displays” highlight the importance of sensory processing and spatial awareness in virtual systems. Visualization and display technologies play a crucial role in presenting immersive content, influencing how users interpret and interact with virtual environments [47]. The presence of “perception” indicates a focus on how users cognitively process visual and spatial information, which directly affects immersion and interaction quality [48]. Similarly, “navigation” is essential for enabling users to move effectively within virtual spaces, impacting spatial orientation and task performance [49]. The inclusion of “simulation” and “reality” further suggests applications in training and experiential environments. However, this cluster indicates that research is often centered on technical and perceptual aspects, with less emphasis on integrating these elements into broader interaction design and user experience considerations.

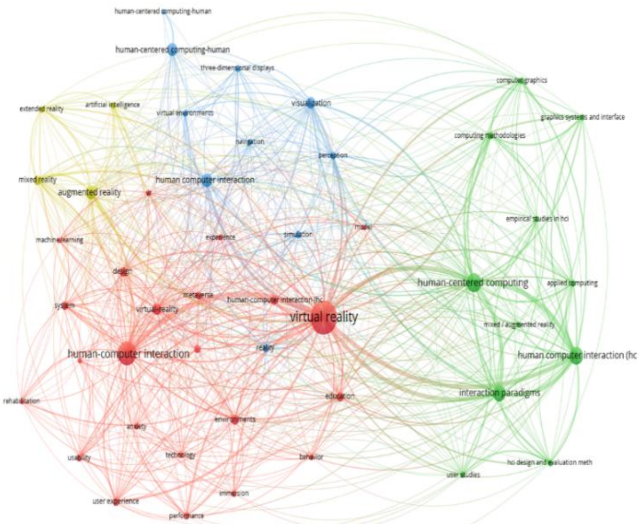

Fig. 4. Co-occurrence keyword network analysis visualization.

Cluster 4 (Yellow), consisting of 4 keywords, represents emerging and enabling technologies in immersive environments, including “artificial intelligence”, “augmented reality”, and “extended reality”. These keywords highlight the evolution of immersive systems toward more adaptive, intelligent, and hybrid environments [50], [51]. The presence of “artificial intelligence” suggests the integration of intelligent systems to enhance interaction, personalization, and automation within virtual environments. Meanwhile, “augmented reality” and “extended reality” indicate the convergence of physical and virtual spaces, expanding the scope of immersive technologies beyond traditional VR. Although this cluster reflects the future direction of immersive research, it remains relatively small, suggesting that the integration of these technologies into mainstream interaction design and evaluation is still emerging. This highlights the need for further research to ensure consistency, usability, and seamless interaction across different immersive platforms.

As shown in Table IV, the four clusters illustrate a comprehensive yet segmented thematic landscape of research in Human-Computer Interaction (HCI) within Immersive Virtual Reality (IVR), encompassing core system design and user experience (Cluster 1), human-centered interaction approaches (Cluster 2), perceptual and spatial interaction processes (Cluster 3), and emerging immersive technologies (Cluster 4). While each cluster represents a distinct and well-established area of study, the relationships among them remain only partially integrated. Key elements such as interaction design, usability, visualization, and emerging technologies are often explored within separate research streams rather than as interconnected components of a unified framework. This indicates that, although the field has matured across multiple dimensions, there is still a need for more cohesive approaches that link system development, user interaction, and technological advancement. Strengthening these connections is essential for advancing IVR research toward more comprehensive, user-oriented, and effective immersive systems.

TABLE IV. SUMMARY OF CO-OCCURRENCE CLUSTERS ANALYSIS ON HUMAN-COMPUTER INTERACTION FOR IMMERSIVE VIRTUAL REALITY

Cluster No & Color	Cluster Label	Number of Keywords	Representative Keywords
Cluster 1 (Red)	Core Interaction, User Experience, and System Design	23	virtual reality; human-computer interaction; user experience; usability; design; system
Cluster 2 (Green)	Human-Centered Computing and Interaction Paradigms	11	human-centered computing; interaction paradigms; user studies; computer graphics; HCI design and evaluation methods
Cluster 3 (Blue)	Visualization, Perception, and Spatial Interaction	10	visualization; virtual environments; perception; navigation; three-dimensional displays
Cluster 4 (Yellow)	Emerging Technologies and Extended Reality	4	artificial intelligence; augmented reality; extended reality

Source. Author’s interpretation derived from VOSviewer analysis

V. DISCUSSION

A. Theoretical Implications

The findings of this study offer several important theoretical contributions to the advancement of Human-Computer Interaction (HCI) within Immersive Virtual Reality (IVR). First, the co-citation analysis demonstrates that the field is strongly grounded in established theoretical frameworks, which are related to presence, cognitive load, and usability evaluation. Foundational works such as presence theory and cognitive workload models continue to serve as the primary conceptual bases for understanding user interaction in immersive environments. However, the dominance of these classical frameworks also suggests that current research remains reliant on theories that were not originally developed for immersive contexts. This indicates a theoretical gap in the development of IVR-specific HCI frameworks that can better account for spatial interaction, embodiment, and multimodal engagement. Second, the keyword co-occurrence analysis reveals that core HCI constructs such as interaction design, user experience, usability, and navigation are frequently studied but often exist as separate thematic domains rather than as an integrated theoretical model.

While interaction paradigms and human-centered computing emphasize user-oriented design, other clusters focus on perceptual processes or emerging technologies, with limited theoretical linkage across these areas. This fragmentation suggests the absence of a unified conceptual framework that systematically connects system design, user perception, and interaction outcomes within IVR. Furthermore, the findings highlight an imbalance between theoretical development and technological advancement. While emerging technologies such as artificial intelligence and extended reality are gaining attention, their integration into existing HCI theories remains underdeveloped. As a result, current theoretical perspectives may not fully capture the complexity of interaction in next-generation immersive systems. Therefore, this study contributes by emphasizing the need for holistic and integrative theoretical models that bridge foundational HCI principles with the unique characteristics of immersive environments, including real-time interaction, spatial navigation, and user embodiment.

B. Practical Implications

In addition to theoretical contributions, this study provides several practical implications for designers, developers, and researchers involved in IVR system development. First, the findings highlight the importance of adopting a user-centered and integrated design approach. The fragmentation observed across usability, interaction design, and navigation suggests that these components should not be addressed independently.

Instead, designers should consider how these elements interact collectively to influence overall user experience, ensuring that immersive systems are intuitive, efficient, and engaging.

Second, the continued reliance on traditional evaluation tools, such as usability scales and cognitive workload measures, indicates the need for more context-specific evaluation frameworks tailored to IVR environments. Practitioners should be cautious when applying conventional methods, as they may not fully capture immersive interaction characteristics such as spatial awareness, presence, and embodiment. This highlights the importance of developing and adopting more comprehensive evaluation strategies that reflect the complexity of user interaction in virtual environments.

Third, the emergence of technologies such as augmented reality, artificial intelligence, and extended reality suggests that future IVR systems will become increasingly complex and adaptive. As such, developers should prioritize interaction consistency and seamless user experience across platforms when integrating multiple technologies. Ensuring compatibility and coherence in interaction design will be critical for maintaining usability and user satisfaction in hybrid immersive systems.

Finally, the findings underscore the importance of aligning technological capabilities with user needs and application contexts. The presence of keywords related to domains such as education indicates that IVR is being applied across diverse fields. Therefore, practitioners should adopt context-aware design strategies, tailoring interaction techniques and system features to specific user groups and application requirements. By doing so, IVR systems can achieve greater effectiveness, usability, and real-world impact.

VI. Conclusion

This study provides a comprehensive bibliometric analysis of research trends in Human-Computer Interaction (HCI) within Immersive Virtual Reality (IVR) by integrating co-citation and keyword co-occurrence analyses. The findings reveal that the field is underpinned by well-established theoretical foundations such as presence, usability, and cognitive workload, while simultaneously expanding toward application-driven research and emerging immersive technologies. The co-citation analysis highlights the continued influence of foundational studies, indicating the field's reliance on classical frameworks, whereas the keyword co-occurrence analysis uncovers dominant research themes related to interaction design, user experience, visualization, and extended reality. Despite this progress, the results demonstrate a notable fragmentation across research domains, where key components such as usability, interaction design, navigation, and user experience are often investigated independently rather than as part of an integrated framework. This lack of cohesion suggests that current research has yet to fully address the complexity of interaction within immersive environments.

In addition, the reliance on traditional evaluation models and the limited integration of emerging technologies into existing theoretical perspectives further highlight critical gaps in the field. Overall, this study contributes to the literature by providing a structured and data-driven understanding of the research landscape in HCI for IVR. It identifies key knowledge bases, thematic developments, and existing limitations, thereby offering a foundation for future research aimed at developing more integrated, user-centered, and context-aware approaches to immersive system design and evaluation.

VII. Future Work

Building on the findings of this study, several directions for future research can be identified. First, there is a need to develop integrated HCI frameworks specifically tailored to immersive virtual environments, which systematically connect usability, interaction design, navigation, and user experience into a unified model. Such frameworks should account for the unique characteristics of IVR, including spatial interaction, embodiment, and real-time feedback. Second, future studies should focus on designing and validating context-specific evaluation methods that go beyond traditional usability and workload measures. These methods should incorporate immersive factors such as presence, engagement, and spatial awareness to provide a more comprehensive assessment of user interaction in virtual environments. Third, as emerging technologies such as artificial intelligence, augmented reality, and extended reality continue to evolve, further research is required to explore how these technologies can be effectively integrated into HCI design. Attention should be given to ensuring interaction consistency and a seamless user experience across different immersive platforms.

Finally, future bibliometric studies may extend this work by incorporating multiple databases, longitudinal analysis, or advanced techniques such as topic modeling and citation burst analysis to capture more dynamic research trends. Expanding the scope of analysis would provide deeper insights into the evolution of HCI research in IVR and support the development of more robust and comprehensive research directions.

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