From Zero to Hero: A Scoping Review of the Emergence of the Metaverse in the Virtual Environments History

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Abstract

The metaverse has transitioned from a science fiction term to a rapidly growing area of research and application, with potential uses in education, professional training, social events, and the virtual economy. However, despite this progress, a fully realized and functional metaverse is not yet available, and its development still requires a clear understanding and definition of the research directions to follow. Nonetheless, the metaverse topic does not start from scratch; it shares its foundations with Virtual Environments (VEs), which represent the Virtual Reality applications' core. In this paper, we built on top of the knowledge given by the history of the two topics to present a scoping review of the historical development of research in VEs and the metaverse from the 1990s to early 2024, analyzing 352 papers from the Scopus database. We aimed to offer a comprehensive understanding of how past research informs the present and future directions of the metaverse. Our findings revealed that the metaverse, while emerging as a distinct research area in recent years, is deeply rooted in the history of VEs, with many of its concepts and technologies deriving from earlier work in the field. We also identified new, underexplored trends within the metaverse research, proposing a future research agenda informed by the shared history of the two topics.

Keywords: Metaverse, Virtual Environments, Scoping Review, Immersive Technologies, 3D Worlds

1 Introduction

History is the best teacher: learning from the past of research can be the key to avoiding repeated errors, understanding and anticipating future directions and trends, which is particularly useful when witnessing notably rising phenomena. In this regard, today, the metaverse is capturing attention like never before: the concept of immersive, interactive, and realistic virtual worlds is recently gaining significant traction in the Virtual Reality (VR) research community due to its versatility and the many potential application contexts researchers envision them. Although initially born as a science fiction term (Stephenson, 1992), the metaverse concept gradually materialized, eventually becoming a reality. To date, while there is no universally agreed-upon definition for the term, the metaverse can be generally defined as a three-dimensional online environment where users interact with each other in real time within virtual spaces represented by avatars (Ritterbusch & Teichmann, 2023). With this general definition alone, it is already possible to envision the potential that it holds in numerous contexts, such as supporting distance learning activities (Wagner, Piovesan, Passerino, & de Lima, 2013; X. Zhang, Chen, Hu, & Wang, 2022), providing simulated and safe spaces for professional training (Koo, 2021; H. Lee, Woo, & Yu, 2022) and serving as a foundation for a new space for creation, sharing, and virtual economy for users (L.-H. Lee et al., 2021). These are just a few of the many areas where research explores how to apply the metaverse effectively.

Notably, the concept of the metaverse has not emerged out of nowhere but it has deep roots in the history of VR and Virtual Environments (VEs), evolving from the research and before becoming a standalone context (Eno, Gauch, & Thompson, 2009; H. Wang et al., 2023). Indeed, the metaverse shares many characteristics with VEs and it can be seen as a natural evolution of these earlier technologies. VEs represent the software part of VR applications and are virtual spaces that simulate real or imagined environments, where users can interact at varying levels of immersivity (Blom & Beckhaus, 2014). Research on VEs has long focused on aspects like immersive experiences (Heldal et al., 2005), interaction models (Frees, 2010), and simulation technologies (John, 2008). The metaverse builds on such foundation, expanding VEs into a more interconnected and persistent online space (Al-Ghaili et al., 2022; L.-H. Lee et al., 2021). VEs and the metaverse are closely related, with VEs providing the technological and conceptual groundwork for the metaverse. Consequently, the vision of interconnected and persistent virtual spaces has become a central area of interest, reflecting the shift of research and development efforts toward the metaverse field (Rejeb, Rejeb, & Treiblmaier, 2023; Ritterbusch & Teichmann, 2023).

Although we are increasingly exploring the metaverse in both literature and media, it has yet to become a practical reality in everyday life due to the absence of a concrete space and feasible solutions (Dolata & Schwabe, 2023). Such an absence has been evidenced by the limited traction on a large scale that metaverse-related project proposals from major companies have received, highlighting a gap between this technology's significant potential and its realization and applicability in real-world contexts (L.-H. Lee et al., 2021; H. Wang et al., 2023). For these reasons, to fully realize the potential of the metaverse, it is essential to deepen understanding of current research and explore promising future directions. To do so, we believe it is essential to analyze the context from which the metaverse emerged and the research path so far; therefore, history will be our best teacher in this endeavor.

In light of the considerations discussed above, the aim of our work was to analyze the history of research in the context of the metaverse to obtain a clear, up-to-date overview of the field informed by its history. Specifically, we defined our problem through two main research questions:

RQ$_1$. *What has been the historical development of research in the fields of Virtual Environments and the metaverse from 1990 to date?*

RQ$_2$. *How has the topic of the metaverse emerged and distinguished itself throughout the history of VE research?*

To answer our research questions, we conducted a scoping review, particularly suited for analyzing literature with a broad scope (Tricco et al., 2018), from the 1990s to the present. Specifically, the research objectives formulated to operationalize those questions have been:

- **Objctive 1: provide a complete timeline** summarizing the history of research linking VEs and the metaverse from the 1990s to early 2024, offering an analysis of the thematic evolution of works in these two fields;
- **Objctive 2: outline the transition** of the context to the modern-day metaverse, analyzing how and when it emerged in the literature as a standalone topic and the current state of the art.

In summary, by advancing the thesis of VEs as the conceptual basis from which the metaverse emerged and evolved, we aimed to conduct a historical analysis from the 1990s to present and examine the intersection of these two domains. The chosen period coincides with (1) the time during which research in the context of VEs became substantial and (2) the period when the term "metaverse" first appeared. Then, we conducted two thematic analysis to cluster and analyze the collected works.

The paper is organized as follows: Section 2 provides a theoretical background on VEs and the metaverse, along with related works. Section 3 details the methodology used for the review. Section 4 presents the findings and the complete timeline. Section 5 discusses the implications and suggests future research directions. Section 6 highlights the study's limitations and Section 7 concludes with potential future developments.

2 Background & Related Work

In the following, we provide the theoretical background necessary to understand the two main themes of our scoping review. Therefore, we first define the context of VEs and their main aspects; then, we move on to the current definition of the metaverse, its main components, and what characterizes and distinguishes it from its predecessors. Subsequently, we discuss the related work identified for our research and highlight the identified research gap.

2.1 Virtual Environments

In the context of VR and immersive technologies, a virtual environment refers to a computer-generated space that users can interact with seemingly real or physically through typical input devices or special electronic equipment, such as VR headsets, motion trackers, or haptic devices (Hale & Stanney, 2014). Such an environment, usually modeled in a three-dimensional way, can simulate physical presence in places in the real world and imaginary worlds and is typically rendered in real time to provide users with an immersive experience (Blom & Beckhaus, 2014; Hale & Stanney, 2014).

In experiments reported in the literature, a VE is typically designed for a particular scenario, providing the user with an immersive experience for a given context. Among the fields where they have been most explored is education, where they have been extensively studied to see to what extent they can increase learning outcomes for various educational activities (Ragan, Bowman, & Huber, 2012; Ragan, Sowndararajan, Kopper, & Bowman, 2010). Moreover, their realistic and simulation potential has made them the subject of many training scenarios for various activities to train in a realistic, interactive, yet protected environment (Smith & Ericson, 2009; Q. Wang & Li, 2004). Along the same lines, the potential of VEs has also been widely explored in the medical context (John, 2008), applying them both as an enhancement of medical training (Bridge, Appleyard, Ward, Philips, & Beavis, 2007; Johnsen et al., 2005) and as a tool to assist in the therapy of patients (de Oliveira et al., 2016; García-Batista et al., 2020).

To achieve realistic and immersive experiences, the design and implementation of VEs must consider some core aspects, such as the design and creation of 3D scenarios and real-time infrastructures. The main focus in this area is to study techniques and frameworks that promote the development of this type of technology (S.E. Chen, 1995; Y. Kim, Yun, Yun, Kwak, & Ihm, 2024), especially addressing the issue of the excessive amount of time and resources required to create 3D environments (López, Cunningham, Ashour, & Tucker, 2020; Shum & Szeliski, 2000). Furthermore, specific focuses have emerged for their implementation, such as studying ad-hoc interaction techniques, which must consider using less intuitive devices and the realistic manipulation of virtual elements (Frees & Kessler, 2005; Mine, Brooks Jr, & Sequin, 1997). Moreover, there is also the concept of the sense of presence within VEs, which indicates how much a user feels present within the virtual space they are immersed in (Nowak & Biocca, 2003), and which represents a crucial factor the user experience in such environments (Cadet & Chainay, 2020; Takatalo, Nyman, & Laaksonen, 2008).

2.2 The Metaverse

In the actual conception that the context has taken in recent years, the metaverse can be defined as a persistent and interconnected 3D world that can be explored and interacted with in real time (Ritterbusch & Teichmann, 2023). Users act within this world through their own highly customizable virtual representation called "avatar" (L.-H. Lee et al., 2021). Such an avatar should aim to be as synchronized as possible with the user in order to achieve realistic interaction.

In order for a metaverse platform to exploit its potential fully, Dionisio, Burns, and Gilbert (2013) identified four key characteristics: (1) the metaverse must offer a high level of realism, engaging users through immersive sensory experiences such as sight, hearing, and touch, fostering emotional and psychological involvement; (2) the metaverse must achieve ubiquity, i.e., it should be widely available and accessible across various devices, anytime; (3) the metaverse must strive for interoperability, which involves smooth information exchange among different virtual worlds; (4) the metaverse must be scalable to support a large number of concurrent users without sacrificing system efficiency or user experience. To sum up, the immediate outcome of the definition phase envisions the metaverse as a persistent and perpetually accessible structure that connects different virtual worlds, enabling data exchange among them. Although its implementation status is far from its definition at present, research is moving towards making it a reality (L.-H. Lee et al., 2021).

Given the overall picture depicted above, it becomes noticeable how the metaverse is evolving as a distinct entity while still sharing fundamental concepts with VEs—such as the 3D virtual worlds at the core and a focus on immersivity and engagement. In contrast to traditional VEs, the metaverse aims for a more comprehensive role, seeking to become not just a virtual space but an entire ecosystem. The metaverse should facilitate a seamless communication and data exchange between virtual worlds (Dionisio et al., 2013), emphasizing social interaction and collaboration (Davis, Murphy, Owens, Khazanchi, & Zigurs, 2009). Moreover, the metaverse aims to establish its virtual economy, allowing users to create, buy, and sell goods and services within its spaces (Y. Chen & Cheng, 2022). Such an economic aspect is currently being supported by emerging technologies, e.g., blockchain and cryptocurrencies (Gadekallu et al., 2022), enhancing the sense of an autonomous virtual society. On the same line, the metaverse emphasizes continuity and persistence, where actions and changes have a lasting impact, eventually envisioning a decentralized system where users have greater autonomy and control over virtual interactions (L.-H. Lee et al., 2021). Ultimately, this shift toward an actual virtual society highlights the metaverse's ambition to act as more than just a digital playground; instead, it conceives a fully realized virtual world with its own economic and social structures.

2.3 Related Work

With the rising research interest surrounding the metaverse over the past few years, numerous exploratory and analytical studies have emerged in the literature, aiming to provide initial comprehensive insights into the state of the art. To understand the state of research in this regard and to grasp how and to what extent research has explored the emerging phenomenon of the metaverse to date, as well as to pinpoint the gaps to address, we identified related research studies which primarily focus on the metaverse, its definition and components, and potential future trends and open challenges. We selected literature analyses that provided a general and panoramic overview of the topic, excluding those not dealing with literature reviews or surveys or focusing on more restricted sub-aspects, to enable a more relevant comparison with our work.

The set of the collected related works, a brief description of each, and the further contribution we aim to make with our research are summarized in Table 1. Such researches on the metaverse used diverse methodologies and perspectives. Ritterbusch and Teichmann (2023) aimed to derive a clear definition of the metaverse, focusing on uniting common foundations across fields. Initial overviews are provided by Rejeb et al. (2023) and Dolata and Schwabe (2023), including a bibliometric analysis and an exploration using the Social Construction of Technology theory. Comprehensive reviews are offered by H. Wang et al. (2023), Venugopal, Subramanian, and Peatchimuthu (2023), and D. Wu et al. (2023), presenting state-of-the-art pictures and theoretical frameworks. Additionally, high-level overviews of the metaverse's origins are outlined by Al-Ghaili et al. (2022) and Ramadhan, Suryodiningrat, and Mahendra (2023), tracing significant milestones and events.

The analysis of related work has highlighted various perspectives and methodologies through which the context of the metaverse has been examined. In such analyses, the identified gap pertains to the lack of a study that examines the metaverse from its earliest mentions, not only as an emerging phenomenon but also in relation to the broader context of VEs for VR, from whose foundations and technologies it is becoming a feasible reality. Our study sought to address this gap by providing a comprehensive historical overview, including the analysis of early works on VEs and tracing the evolution of research until the emergence of the metaverse as a standalone theme. We aimed to contribute to the knowledge already provided by the related works with a broader and more in-depth understanding of the metaverse evolution, offering an important historical foundation for future investigations in the field.

3 Methodology

We conducted a scoping review. The process followed the extended PRISMA guidelines for scoping reviews, i.e., the PRISMA-ScR approach proposed by Tricco et al. (2018) with semi-automatic extensions.

Research Questions. We started by defining our research questions. Our first RQ was formulated as follows.

> **$\mathbf{RQ_1}$.** What has been the historical development of research in the fields of Virtual Environments and the metaverse from 1990 to date?

We were interested in outlining the history of research in the broader field of VEs, their development, and their applications over time. To achieve this, we have established a decade as the temporal unit of measure to analyze and divide the different historical phases of the research, starting from 1990 up to 2024. Such time window was selected for two reasons: (1) we were interested in analyzing the evolution of the metaverse from its first appearance as a science fiction term to the present day, thus covering the period starting from its initial mention in 1992 (Stephenson, 1992); (2) based on our analysis, the period before 1990 discussed early prototypes and applications of VEs that are highly different from those known today. Additionally, it is after these years that research in this context became established on a large scale.

As an immediate follow-up research question to the one mentioned above, within the research history we have gathered, we defined $\mathrm{RQ_2}$.

Paper	Brief description	Our further contribution
Al-Ghaili et al. (2022)	Review of metaverse literature to provide a historical overview, discus its definition, architecture, and applications, and suggest a framework for addressing ongoing challenges	Enhance the historical overview by analyzing in more detail and in conjunction with the VEs context
Ritterbusch and Teichmann (2023)	Systematic Literature Review that extracts a definition for the metaverse based on those found in the literature	Building upon this knowledge of the term's definition and expanding it to a more comprehensive overview of the topic
H. Wang et al. (2023)	Survey that provides a comprehensive metaverse overview by summarizing its development, characteristics, technological framework, and challenges	Enrich the provided knowledge on the development and challenges with insights derived from the analysis of past trends in the histories of both the metaverse and VEs
Rejeb et al. (2023)	Study that employs bibliometric and topic modeling techniques on metaverse journals to uncover trends and most active authors and venues in the field	Deepen the analysis beyond bibliometric data by providing deeper insights into the retrieved research papers and their thematic
Venugopal et al. (2023)	Survey of metaverse literature to to propose a hypothetical meta-stack framework for understanding its components, cutting-edge technologies and research challenges	Expand the research focus to provide more history-aware insights and considerations for the past and current state of the metaverse and future research trends and directions
Ramadhan et al. (2023)	Review that covers the preliminary information on the metaverse, its origin, components and usage	Delve deeper into the analysis of the metaverse foundations and current trends to provide a broader overview of the topic and its evolution
D. Wu et al. (2023)	Survey that assesses the state of the art of the metaverse and proposes a technical framework for its development	Contribute to the proposed frameworks with additional insights and future research agenda derived from our review
Yang, Li, Gan, Chen, and Qi (2023)	Survey that argues for a human-centric approach to the metaverse, discussing its construction and possible related issues and challenges	Broaden the research focus beyond a solely human-centric metaverse type to encompass future research directions and guidelines of a more generalized nature
Dolata and Schwabe (2023)	Study that uses the Social Construction of Technology theory to clarify conflicting notions of the metaverse and highlight its evolution	Contribute to expanding the understanding of the concepts and evolution highlighted, moving beyond the scope of the Social Construction of Technology Theory
Tukur et al. (2023)	Scoping Review covering the post-COVID-19 period to explore and evaluate the challenges, privacy and security issues of the metaverse	Extend the temporal scope to encompass a broader post-COVID period, while also exploring in more detail the implications of the metaverse, given its historical context

Table 1: Summary of the Related Work

RQ$_2$. How has the topic of the metaverse emerged and distinguished itself throughout the history of VE research?

With this research question, we were interested in focusing on the emergence of the metaverse theme, tracing its development, correlation, and points of distinction with the broader topic of VEs. In other words, the two RQs aim to provide different perspectives on the shared history between the two topics. On the one hand, RQ$_1$ aims to provide a horizontal overview of the entire history of VEs and the metaverse, analyzing the published works decade by decade. RQ$_2$, on the other hand, seeks to obtain a vertical overview of the papers that have addressed the metaverse to understand how this topic has developed, its points of contact with the broader history, and how it is differentiating and evolving.

Data Source Selection. To conduct our scoping review, we chose Scopus as our data source, a choice consistent with other related reviews (Eskandari & Motamedi, 2024; Liberatore & Wagner, 2021; Linares-Vargas & Cieza-Mostacero, 2024). We based our decision on two main motivations: first, given the broad scope of our research, we selected a source that aggregates various sources—Scopus indeed contains scientific articles from multiple publishers; second, it provided robust bibliometric tools for analyzing our results. For these reasons, we chose to reconstruct the history by considering all the material indexed on Scopus from the 1990s to the present.

Search String Design. We defined the terms for the search string based on the two areas in which we were interested in analyzing the history. The first area concerned the history of VR, with a specific focus on the associated virtual environments. The second area concerned the metaverse, for which we had no particular constraints to narrow this field. Therefore, the keywords identified were *metaverse*, *virtual reality*, and *virtual environment*.

Search String
TITLE-ABS-KEY("metaverse" OR ("virtual realit*" AND "virtual environment*")*

To capture both simultaneously, we constructed the string by placing the two fields in OR, while to capture the correlation between VR and VEs, we placed the two keywords in AND. Asterisks were added to ensure we could also capture works with slight variations of these keywords—e.g., plurals—and the search was conducted by title, abstract, and keywords. We note that the initial core query was intentionally generic but anchored to the two main topics, in order to manage both the breadth and the historical comparability of our dataset.

The entire process of identifying and selecting articles is outlined in Figure 1. Additionally, we made all the results obtained from this phase available in our online appendix (Pentangelo, Gravino, & Palomba, 2024).

Elegibility Criteria. After defining the keywords to query the database, we established eligibility criteria that the papers needed to meet. We integrated these criteria as filters on Scopus to automatically exclude papers that did not meet them. The criteria are listed and explained in Table 2.

ID	Criterion	Rationale
EC1	*The paper's publication date must be between 1990 and 2024*	We set the time filter to capture the research period that aligned with our analysis objectives.
EC2	*The paper must belong to the subject area of Computer Science or Engineering*	We were interested in reconstructing the history from a perspective primarily related to Computer Science, but we also extended our scope to include Engineering due to the potentially strong correlation between the two areas
EC3	*The paper type must be Article or Conference Paper*	We were only interested in officially published literature
EC4	*The paper must be written in English*	We were only interested in papers written in English

Table 2: Elegibility Criteria for the research

First screening of the Results. The results of the search string, run in February 2024 with the eligibility criteria filters applied, yielded a total of 26,499 results. We exported the data from this initial result set and performed additional screening operations to refine the selection. To manage this substantial number of papers for screening, we adopted a dual approach for their evaluation: (1) a semi-automatic assessment based on the title, abstract, and publication venue, and (2) a subsequent manual review of the papers resulting from the initial screening.

To conduct an initial extensive screening of all the results retrieved from the search string, we defined a semi-automatic strategy to manage the large volume of articles obtained. The automated part of this phase involved analyzing the title and abstract using checks to verify their suitability for our research questions. This strategy was based on four factors:

1. *Duplicates removal.* All duplicate papers were removed from the selection. This included the exclusion of the same work published and indexed in two different venues, or short or summary versions of the same complete works.
2. *Number of citations.* For papers before 2020, we considered that a paper must have at least one citation to be considered, ensuring a minimum level of historical relevance. This criterion was not applied to recent works to avoid bias toward contemporary works and trends that have yet to have time to be cited in new articles.
3. *Abstract relevance.* To ensure a minimum relevance to the topic and mitigate the breadth of the search string, we filtered abstracts to exclude, a priori, all works captured by the search that did not primarily address VEs and the metaverse, their development, and applications. To achieve this, we defined a list of keywords to capture further works that could answer our research questions. The list of words used is shown below and was designed to recognize any abstract that explicitly mentioned at least one of these expressions.

> **Filter Keywords**
> *"virtual environment*", "3D world*", "digital environment*", "3D environment*", "metaverse*", "virtual world*", "digital world*"*

4. *Venue*. We evaluated the papers based on the publication venue, following the metrics of Google Analytics for the list of the most relevant venues in the field of Computer Science, particularly for the subcategories of Human-Computer Interaction[1], Computer Graphics[2], and Multimedia[3]. However, this analysis was not an automatic filtering process and we set the venue criterion as never rigid: all papers were also subject to manual relevance checks, and contributions from less visible outlets were retained whenever they aligned with our research questions. By doing so, works that did not fall within one of these venues were still subjected to the previous relevance tests, excluding a priori only those venues entirely out of scope for our research.

All the papers selected by the automatic process then underwent a manual relevance check of the title and abstract, which further led to the exclusion of other irrelevant papers. At the end of the first screening process a total of 490 papers were selected for the quality assessment phase.

Second screening of the Results. The papers selected in the initial screening phase were finally subjected to a manual quality assessment of their full text. In this final operation, the papers that would be definitively included for the data analysis of our scoping review were selected. From this second manual screening of the paper content, all papers that met the following criteria were excluded: (1) did not have one of the two areas of interest, namely VEs or metaverse, as their main topic, (2) were duplicates or summaries of existing works and did not advance the state of the art in any way, and (3) the overall quality of the article was not convincing in terms of form, structure, and report of the work conducted. At the end of this process, 138 papers were further excluded. At the end of this selection process, **a total of 352 papers were included** in the scoping review.

Thematic Analysis. Once the papers were collected, we used thematic analysis to analyze the selected studies. To conduct the analysis, we relied on the framework provided by Maguire and Delahunt (Maguire & Delahunt, 2017) which in turn builds upon the seminal six-phase approach by Braun and Clarke (Clarke & Braun, 2013). This analysis focused on identifying themes and common areas among the various works to categorize them into common groups for discussing our results. Table 3 summarizes the steps and how they were performed in our analysis. The process was applied to capture the evolution of themes over time, so to answer RQ_1.

Concerning Step 1-3 of the framework, we started by familiarizing ourselves with the collected papers to be clustered. To achieve this, we engaged in a manual process where each paper was annotated with an original short summary. This stage was conducted by the first author, who systematically read and annotated each paper with summaries, consisting of three to four key sentences, to highlight the paper's specific thematic contribution. From these summaries, the first key thematic points that could unite groups of papers began to emerge. Therefore, observations were made from each of these, which led to the formation of the first thematic clusters. Each iteration of

[1] https://scholar.google.com/citations?view_op=top_venues&hl=it&vq=eng_humancomputerinteraction
[2] https://scholar.google.com/citations?view_op=top_venues&hl=it&vq=eng_computergraphics
[3] https://scholar.google.com/citations?view_op=top_venues&hl=it&vq=eng_multimedia

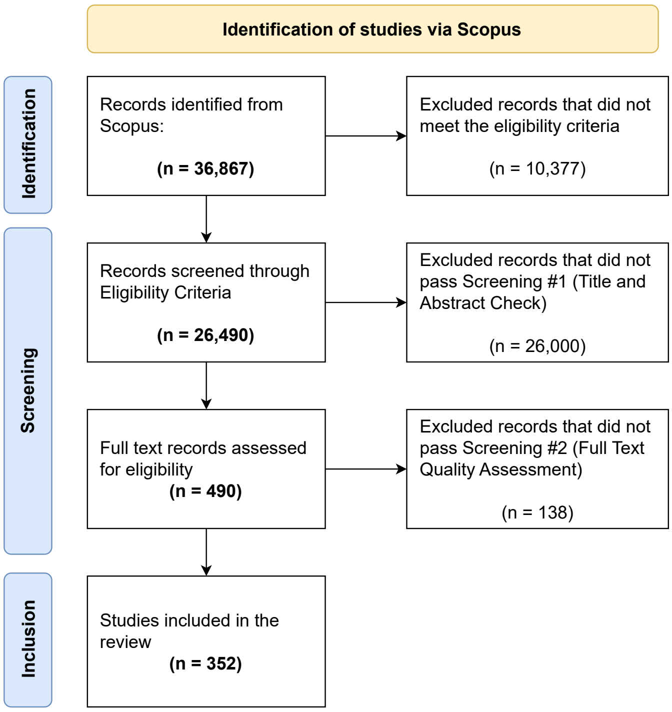


Fig. 1: PRISMA flow diagram.

this phase was then subjected to a validation process involving the other two authors. This was performed with an individual review and refinement phase by each co-author, followed by collective weekly meetings to discuss. These meetings were held until full thematic convergence was reached—specifically, until a total consensus was achieved regarding the labels assigned to each theme and the subsequent refinements proposed by the team. Figure 2 shows an example diagram that was followed for these phases.

Building upon these initial observations, we proceeded by comparing thematic developments across different decades to identify patterns of convergence. The first author identified shared components among the preliminary themes and formulated observations on how these could be consolidated into broader, overarching themes. These proposals were subsequently subjected to collaborative review and discussion in dedicated meetings with the co-authors. During these sessions, the team analyzed the observed patterns to decide whether and how these elements should be aggregated and re-labeled. By observing recurring concepts, we transitioned from specific initial labels to broader, more comprehensive theme. Figure 3 shows a sample of this process.

We repeated this process a second time for papers on the metaverse to answer RQ_2. At the end of these processes, each collected paper was assigned to one category, with each paper being assigned to one and only one category.

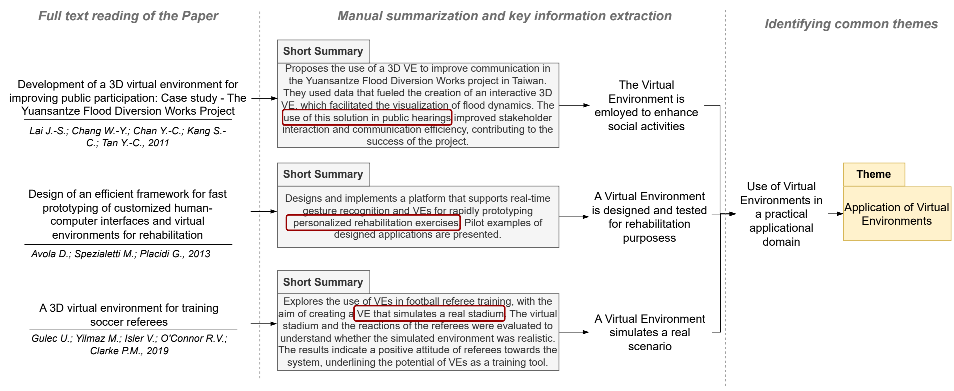


Fig. 2: Outline of the process followed for the first part of the thematic analysis, starting from the drafting of the summaries to the first thematic label.

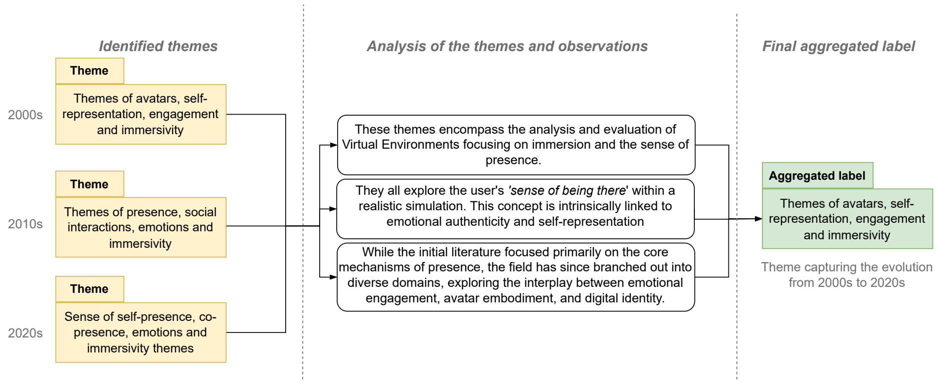


Fig. 3: Outline of the process followed for the second part of the thematic analysis, involving the refinement of the labels and the obtaining of the final themes.

4 Analysis of the Results

This section presents the results obtained to address the two RQs identified. For each RQ, we provide an overview of the results and present the related thematic analysis and collected papers. Finally, we offer a concise answer for each RQ that synthesizes the findings and discussion.

4.1 RQ_1: On the historical development of research in the fields of VEs and the metaverse

The scoping review collected a total of 352 papers, spanning from 1992 to February 2024. To provide a comprehensive temporal overview of the research through these articles, we grouped them into four respective decades: the 1990s, 2000s, 2010s, and the first four years of the 2020s. For each of these four clusters, we conducted a thematic

#	Framework Phase	How it was performed in our study
1	Familiarization with the data	Each of the 352 papers was read in its entirety. To ensure deep engagement, a cohesive summary was manually drafted for every article, capturing the core findings and theoretical contributions relevant to the research question
2	Generating initial codes	From the summaries and original texts, main thematic categories were identified. These served as initial codes, i.e., labels that captured specific, recurring concepts found within individual papers
3	Searching for themes	The categories identified in Phase 2 were cross-referenced and aggregated based on conceptual similarities. This led to the creation of the first labels, which represent the preliminary themes emerging across the entire datasets
4	Reviewing themes	The themes were refined by checking them against the original summaries and categories to ensure that each category was distinct and that the data within them was coherent. Each of the identified themes across the decades were reviewed and re-assigned into a broader category, which brought together similar themes and captured their evolution over the years
5	Defining and naming themes	The final categories were formally defined to capture the essence of each thematic cluster. Labels were refined to ensure they clearly communicated the specific dimension of the literature they represented
6	Producing the report and writing up	The final themes provided the logical structure for the scoping review's results analysis, which guided the answering of the two research questions

Table 3: Steps of the thematic analysis following Maguire and Delahunt's framework (Maguire & Delahunt, 2017).

analysis that clustered them by common sub-themes. Figure 4 shows the output of these operations and the general overview of the results of our research. Furthermore, Figure 5 shows the number of papers for each year and their respective publication venues.

By observing this preliminary data, one can gain insights into the historical trends of research on VEs and the metaverse. The research began in the 1990s, with some preliminary works proposing the first technologies and prototypes for this context, such as the CAVE project (Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992). Shortly after, it became an established and more extensively explored field, as evidenced by the increase from 16 papers in the 1990s to 100 in the 2000s. The trend remained relatively stable until the second half of the 2010s when a noticeable decrease in the number of papers collected was observed. The trend began to rise again only in the 2020s, reaching the highest recorded number of collected papers in 2023. This increase is primarily due to publications related to the metaverse, representing the most numerous category in the 2020s with 37 papers. This surge contributed to the total number of collected papers in the early 2020s reaching 102. Concerning the number of citations over the years for the collected papers, Figure 7 shows these numbers for each category over the years. Across all categories, citation counts show a generally consistent upward trend until the second half of the 2010s. Around this period, most categories experience a temporary decline, which is followed by a renewed increase coinciding with the surge of publications on the metaverse. Notably, the Metaverse category displays a particularly steep growth, clearly outpacing the others and reflecting the central role that metaverse-related research has recently assumed.

Regarding the publication venues, Figure 6 shows some statistics about their type and rank. The analysis of venue types (a) shows that the majority of publications were disseminated through journals (213 papers), compared to a smaller yet still significant portion in conferences (139 papers). This suggests a strong preference for journal-based dissemination in the field. When examining venue quality (b), a more nuanced picture emerges. Most journal publications are concentrated in high-impact venues, with a remarkable dominance of Q1 journals (168 papers). In contrast, conference papers are primarily published in highly ranked venues such as A* (58 papers) and in outlets without a formal ranking (52 papers). Moreover, two observations can be made. First, the most targeted venues have remained relatively consistent over the years, with *Virtual Reality Journal* and the *IEEE Virtual Reality Conference* continuing to be the most frequently targeted since 2003. Second, it is immediately noticeable that the others are disparate and highly diverse except for a few more frequent venues. Specifically, each of these venues can be consulted in our online appendix (Pentangelo et al., 2024). Such a divergence could be due to some factors: (1) VEs and the metaverse are closely related to VR technologies, yet their use has been experimented with in a wide variety of contexts, showing broad application potential, as also revealed by the thematic analysis; (2) especially in recent times, with the shift of interest from the more narrowly focused VEs to the metaverse, there are not yet dedicated venues for the topic. These are only now beginning to emerge and have yet to have the opportunity to become established. This has led to a situation where papers on the topic are published based on other themes they address within the works—e.g., education, computer graphics, system design, or HCI.

Following the preliminary data observations, we now move on to discuss the results of the thematic analysis. For each decade, we identified common thematic categories under which each work could be clustered. Each paper was placed into a single category. Additionally, in this phase, to answer $\mathbf{RQ}_1$, all papers on the metaverse were placed in a dedicated category. For the remaining papers, our analysis identified three categories for the 1990s and four for the subsequent decades. Notably, we observed consistency in categories across the decades, which generally remained constant, though they evolved over the years. For this reason, related categories across the decades were coded with the same color, as referenced in Figure 4. Below, we discuss each category and the papers that belong to them, decade by decade.

4.1.1 1990s

The 1990s represented the first significant period in which research studying VEs in the context of VR gained traction. The 16 studies collected during this decade were clustered into three categories, which laid the foundations that would be further

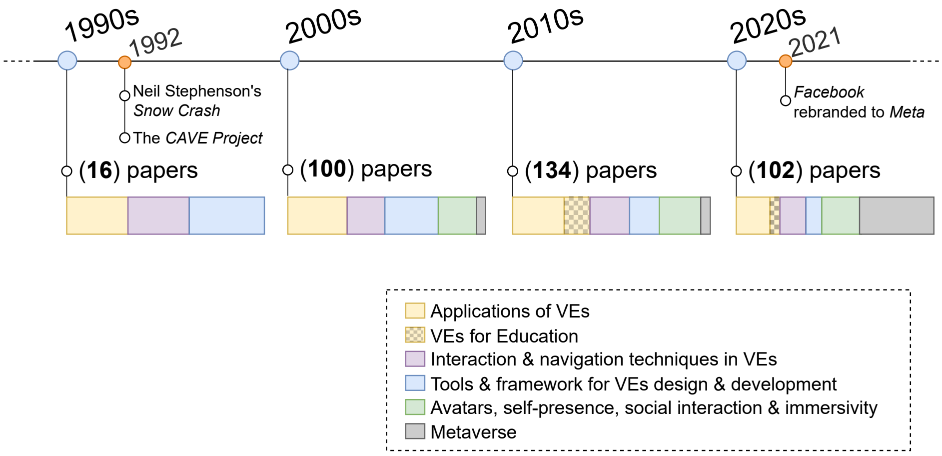


Fig. 4: Timeline of papers collected from 1990 to 2024.

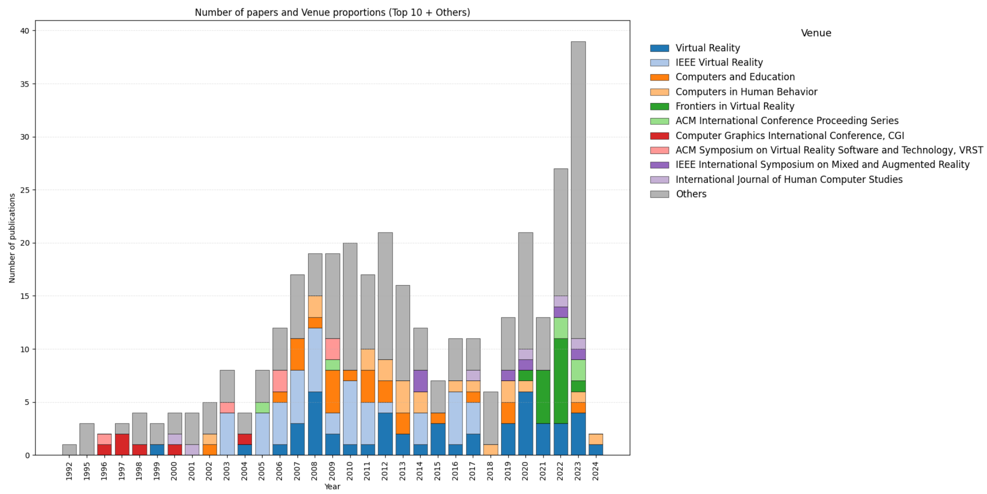
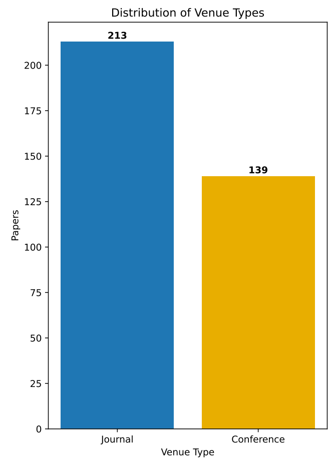


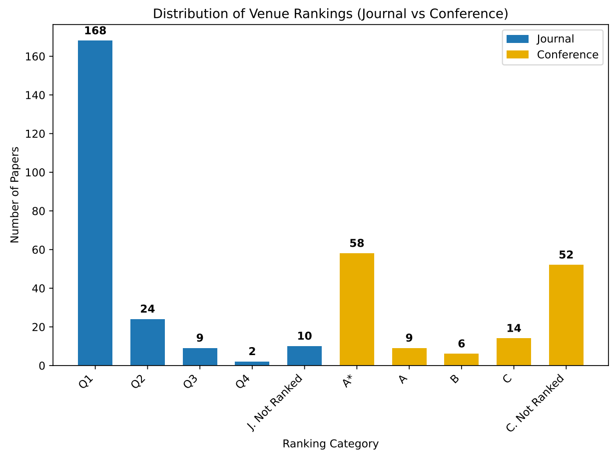
Fig. 5: Publication venues of the papers grouped by year. The plot shows the Top 10 most frequent venues, the remaining ones have been labeled as "Other".

developed and evolved in the following years. During this initial historical period analyzed, many of the key concepts emerged that would remain a constant in research for decades to come. Notably, the papers collected for this decade mark the effective starting point of our scoping review, which resulted to be posterior to Stephenson's novel (Stephenson, 1992), in 1992. Each paper for each category is shown in Table 1.

Applications of VEs. The category includes all those works that have begun experimenting with VEs in various application contexts. Indeed, even in such an early



(a) Distribution of Conference vs. Journals papers



(b) Rank Distribution for Conferences and Journals papers.

Fig. 6: Statistics about collected papers' venues type and rank.

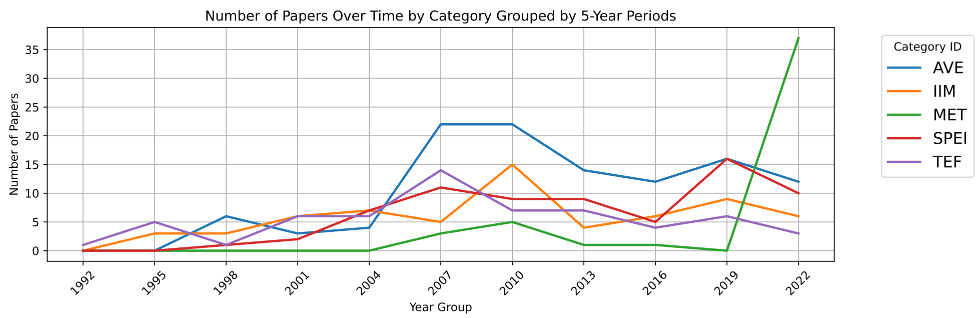


Fig. 7: Total citations over time by category, grouped by 5-year period. The IDs in the legend encode the categories, from top to bottom: Applications of VEs (AVE), Interaction & navigation techniques in VEs (IIM), Metaverse (MET), Avatars, self-presence, social interaction & immersivity (SPEI), Tools & framework for VEs' design & development (TEF).

temporal phase, several areas have emerged where research has aimed to develop, use, and evaluate VEs for different purposes. The works categorized in this section cover various application contexts, demonstrating how research interest in using this technology was immediately evident. Notable examples have been the creation of a digital museum that allowed users to explore and interact with exhibitions virtually (Yura, Usaka, Fujimori, & Sakamura, 1998) or the introduction of interaction techniques in the medical context to analyze patient data in an immersive 3D format (Krapichler, Haubner, Engelbrecht, & Englmeier, 1998). The automotive industry also started to benefit from VEs, as evidenced by Volkswagen's use of VR technologies in vehicle design (Purschke, Schulze, & Zimmermann, 1998). Moreover, VEs were also tested for collaborative work when a VE was tested to communicate and organize teamwork (Tomek & Giles, 1999).

Interfaces and interaction methods. The category includes all works that have begun to study methods of interactions and ad hoc interfaces for VEs. Indeed, the 3D nature of VEs immediately posed a challenge: traditional techniques and interfaces for interacting with 2D software were not applicable in the same way to these technologies. For this reason, studies have started investigating how to interact with virtual objects (Mine et al., 1997), navigate 3D spaces, formulate and compare different techniques (S.E. Chen, 1995; Usoh et al., 1999), and design ad hoc techniques and interfaces to interact with the environments and make the experience seamless (Coninx, Van Reeth, & Flerackers, 1997; Mine et al., 1997). Moreover, the concept of "presence" also emerged, indicating the feeling of being inside a virtual place, having a sense of self and surrounding space (Hendrix & Barfield, 1995).

Generation and rendering algorithm. The category contains works that have focused not only on developing VEs but also on technologies and algorithms that facilitate and improve their design and generation. During the reference period, VEs were an emerging technology not widely disseminated on a large scale, which led to the need to study how to develop and advance them. A memorable study by Cruz-Neira et al. (1992) introduced the CAVE virtual environment, one of the first immersive systems consisting of walls and a floor in a room-sized cube onto which images were projected. Users only needed to wear stereoscopic glasses for viewing and could interact with the VE. Among the proposals and technological advancement of such period, there were QuickTime VR by Apple was able to create 3D VEs from 2D 360-degree cylindrical panoramic images (Zilles & Salisbury, 1995), the use of panoramic images to achieve a fully immersive VE experience (Matos, Gomes, Parente, Siffert, & Velbo, 1997), and rendering algorithms that could generate and interact with virtual elements (Nishino, Nakano, Korida, & Utsumiya, 1996; Pausch, Burnette, Brockway, & Weiblen, 1995). Research also focused on techniques to automatically deform realistic human bodies in VEs, contributing to more lifelike representations in VR applications (Thalmann, Shen, & Chauvineau, 1996).

4.1.2 2000s

The 2000s marked the first decade in which research in the field of VEs experienced a significant surge, as evidenced by the notable increase in the number of studies. The 100 studies collected during this decade were clustered into five categories: three that continue the trends initiated by preliminary research from the previous decade, one new category that investigates the theme of sense of presence within VEs, and the first studies mentioning the metaverse captured by the scoping review. This period saw extensive exploration of VEs, both in terms of design and implementation. Research has proposed many methodologies to create better environments and specific techniques have been studied to improve user experience. Additionally, researchers broadly investigated various application contexts where VEs could be successfully exploited. Each paper for each category is shown in Table 2.

Applications of VEs. The category builds on the one identified in the previous decade and continues to gather works experimenting with using VEs in increasingly diverse contexts. In fact, in the 2000 decade, it represents the most numerous category, highlighting how interest in studying the potential of VEs has increased. Researchers have studied VEs to enhance learning experiences and collaboration (J.X. Chen, Yang, & Loffin, 2003), and virtual campuses within platforms like Second Life have been used for educational and social purposes (De Lucia, Francese, Passero, & Tortora, 2009). In the medical field, VEs have been effective in immersive training systems and simulations (John, 2008; Johnsen et al., 2005), as well as in assisting patients' therapies (Hoffman, Garcia-Palacios, Kapa, Beecher, & Sharar, 2003). VEs have also proven valuable in industrial training processes (Q. Wang & Li, 2004) and for professional training systems (de Haan, Koutek, & Post, 2007). The interest in exploiting them for collaborative design and remote work was also constant (Schnabel, 2002), and they also emerged in studies for entertainment applications (H. Seo et al., 2000) and cultural and historical education promotion (De Amicis, Girardi, Andreolli, & Conti, 2009; Ştefănescu, Căruntu, & Jamt, 2008).

Interaction techniques for VEs. The category includes works that have addressed the problem of interacting with and exploring VEs, continuing the trend that began in the previous decade. In this decade, the focus has been mainly on the interaction and manipulation of 3D virtual objects and movement techniques to simulate navigation within VEs. Collected papers in this category address challenges to enhance user experiences across multiple applications, highlighting the limitations users may encounter while interacting and exploring a VE (Hindmarsh, Fraser, Heath, Benford, & Greenhalgh, 2000; Liu, van Liere, Nieuwenhuizen, & Martens, 2009). Novel tools (Schoenfelder & Spenling, 2005; Willans & Harrison, 2001) and techniques (Frees & Kessler, 2005; Lok, Naik, Whitton, & Brooks, 2003; Steed, 2006) have been proposed to improve precision in manipulating virtual objects, along with methodologies to enhance real-time control of three-dimensional avatars (J. Lee, Chai, Reitsma, Hodgins, & Pollard, 2002). The navigation task has been one of the most explored (Barrera, Takahashi, & Nakajima, 2004; Ruddle & Lessels, 2009; Tan, Gergle, Scupelli, & Pausch, 2006), for which research has tested numerous methods such as landmarks (Jansen-Osmann, 2002), dynamic path calculation (J.S. Yoon & Maher, 2005), and innovative locomotion metaphors and interfaces (Interrante, Ries, & Anderson, 2007; J. Yoon & Ryu, 2006). Lastly, the medical field was crucial again for this category: ad hoc instruments and devices were designed for therapy purposes exploiting VEs (Chua et al., 2003; Jack et al., 2001), proving to be successful in assisting patients with certain medical conditions, such as blindness (Lahav & Mioduser, 2008; Lahav, Schloerb, Kumar, & Srinivasan, 2008).

Tools & framework for VEs' design & development. The category includes all papers that have proposed new frameworks, methodologies, and tools to support the design and development of VEs. We consider this category an evolution of the previous one—i.e., *Generation and rendering algorithm*—as it represents its concretization in a more established sub-field of research, moving from proposals of new rendering algorithms to complete frameworks and ad hoc tools. To address the challenge of speeding up the process of generating 3D VEs, many works have focused on new methods and techniques that could improve and automate such a process (Boukerche, Jarrar, & Pazzi, 2009; Poullis, You, & Neumann, 2008; Shum & Szeliski, 2000; Zeng & Tan, 2007). Research also introduced integration and visualization tools able to exploit VE to represent data from heterogeneous sources (Barsoum & Kuester, 2008; B. Huang, Jiang, & Li, 2001), as well as network and infrastructures tailored for VE applications (Rueda, Morillo, Orduña, & Duato, 2007; Scheffler, Springer, & Froehlich, 2008). Not limited to that, various development and design tools have been proposed that allow users to develop and test 3D objects and virtual worlds (Ingrassia & Cappello, 2009; G.A. Lee, Kim, & Park, 2002; J. Seo & Kim, 2004), along with technologies to design 3D virtual spaces with generative design agents (Gu & Maher, 2005) or 3D interfaces (Andujar, Fairen, & Argelaguet, 2006; Antonya & Talaba, 2007; Taylor et al., 2001). Among the first intelligent interactive systems for generating elements in VEs were also presented, such as frameworks for the generation of avatars and intelligent actors (Liang, Zhang, Liu, & Krokos, 2008; Oyarzun et al., 2009), agent-based software architecture for the creation of VEs for training (Mendez & De Antonio, 2005), and systems to enrich traditional VEs with abstract data (Bowman et al., 2003). Lastly, papers in this category broadly explored educational and collaborative contexts, proposing frameworks for developing and improving educational VEs (Crosier, Cobb, & Wilson, 2002; Ieronutti & Chittaro, 2007) and cooperative and social activities (Kurillo, Bajcsy, Nahrsted, & Kreylos, 2008; Linebarger, Janneck, & Kessler, 2003; Menchaca, Balladares, Quintero, & Carreto, 2005; Méndez, Ocaña, Valderrama, & Arellano, 2005).

Sense of self-presence, co-presence, emotions and immersivity themes. The category includes all works that have addressed the theme of "sense of presence." The concept had emerged in the previous decade; however, in the years now under examination, it has become such a significant research interest that it represents a new category in its own right. Such a theme was investigated under multiple perspectives to determine the factors that potentially have the most influence, such as spatial and distance perception of the user in the VE (Interrante, Ries, & Anderson, 2006; Interrante, Ries, Lindquist, Kaeding, & Anderson, 2008) and scene complexity (Luo, Kenyon, Kamper, Sandin, & DeFanti, 2007). One of the most explored factors is the concept of immersivity—i.e., the degree to which a user feels enveloped and integrated into a virtual space (Heldal et al., 2005). In this regard, researchers studied the role of visuals and audio (Bormann, 2008), media content (Baños et al., 2004), and even scents (Tortell et al., 2007) in making the user feel immersed in the virtual experience and enhance their sense of presence. On this same line, many works examined how users' emotions can be affected and how they impact the experience's immersivity (Bailenson, Yee, Brave, Merget, & Koslow, 2007; Riva et al., 2007; Takatalo et al., 2008). Other factors that impact the sense of presence have been the way users avoid virtual obstacles (Fink, Foo, & Warren, 2007) and position discrepancy between users and avatars (Burns, Razzaque, Whitton, & Brooks, 2007). As an extension of the concept of presence, research has similarly analyzed the sense of "co-presence" and "social presence," which refer to the perception of oneself in relation to other users and virtual agents (Narayan, Waugh, Zhang, Bafna, & Bowman, 2005; Nowak & Biocca, 2003; Ries, Interrante, Anderson, & Lindquist, 2006), also studying how VEs can help with social interactions for people with autism (Parsons, Leonard, & Mitchell, 2006). Lastly, the works also explored a recurrent challenge in applications exploiting VEs: the motion sickness—i.e., the physical discomfort caused by more or less prolonged interaction with VEs and objects—trying to identify potential causes and solutions (Meehan, Razzaque, Whitton, & Brooks, 2003; Nichols, Haldane, & Wilson, 2000; Young, Adelstein, & Ellis, 2006).

Metaverse. The category includes the first three papers that addressed the topic of the metaverse, all published at the end of the decade. These three works were the earliest identified in the entire history of the field to discuss the topic, and they also anticipated some concepts that would become foundational in the following years. For example, the work of Davis et al. (2009) initiated the definition and identification of the primary constructs of the metaverse. Sébastien, Conruyt, Courdier, and Tanzi (2009) also began to propose the first potential systems to support the implementation of metaverse platforms. Finally, Eno et al. (2009) anticipated the theme of user-generated content (UGC), highlighting the potential for users within the metaverse to create customized virtual content. The presence of these works years before the explosion of the metaverse trend is notable, as is how the topic is addressed, which precisely anticipated how future studies would examine the subject.

4.1.3 2010s

The 2010s continued and evolved the research outcomes of the previous decades. The 134 studies collected during this decade were clustered into three categories—plus a new subcategory—continuing the trends observed in the previous decade while evolving and expanding them to include new concepts. For instance, during such a period, the term "avatar" gained traction and became more frequently used to refer to the user's representation within the virtual world. The first half of this period confirms the positive trend of increasing research interest in the field; nonetheless a negative trend was registered by the second half of this decade. The reasons behind this negative trend might be attributed to a combination of factors. On the one hand, research on VEs had reached a degree of maturity by the end of 2010s, with fewer new questions emerging and the main categories stabilizing over time, leading to a relative plateau in scientific output. On the other hand, this period coincided with a decline in industry and investment interest, as the initial hype surrounding VR was tempered by high costs, hardware limitations, and a lack of compelling content, a dynamic that can be interpreted as a "trough of disillusionment" consistent with the Gartner Hype Cycle (Dedehayir & Steinert, 2016). Importantly, we interpreted this downturn not as a real loss of interest but rather as a transitional phase. Our analysis of citations (Figure 7) shows that all categories experienced a slowdown in the late 2010s. Indeed, concerning the number of papers mentioning the metaverse, it still remains very limited by the end of these years. Each paper for each category is shown in Table 3.

Applications of VEs. The category continues the exploration of VEs in various application contexts, advancing the research trend seen in both previous decades. The potentiality of exploiting VEs for collaborative activities has been further investigated, proposing new environments for multi-user and multi-modal communication and collaboration (Chertoff, Goldiez, & LaViola, 2010; Doumanis, Economou, Sim, & Porter, 2019; Lai, Chang, Chan, Kang, & Tan, 2011), cooperative simulation scenarios (Maciel et al., 2011), and even virtual conferences (Buthpitiya & Zhang, 2010; Sharma & Schroeder, 2013). The medical field remained one of the most explored, introducing systems and tools able to assist in patients' rehabilitation in varied medical conditions (Cavalcante, Júnior, Cardoso, Soares, & de Lima, 2018; de Oliveira et al., 2016; Lahav, Schloerb, & Srinivasan, 2015), by offering daily training environments (Guidali et al., 2011; Gulec, Yilmaz, Isler, O'Connor, & Clarke, 2019), immersive and personalized exercises (Avola, Spezialetti, & Placidi, 2013; Feasel, Whitton, Kassler, Brooks, & Lewek, 2011). VEs also kept great potential in industrial and professional training fields, with research experimenting with them in assembly operations (Hongmin, Dianliang, & Xiumin, 2010; Puthenveetil et al., 2015), training of professionals (Aleotti & Caselli, 2011; Carvalho et al., 2016; E.H. Tanaka et al., 2017), design and manufacturing (Alvarez & Su, 2012; Vosniakos & Gogouvitis, 2015), and even design of environments for risk prevention (Camus, Lenne, & Plot, 2012). Another continued and expanded trend concerned the use of VEs for disseminating awareness about historical and cultural heritage (Damiano & Lombardo, 2016; Marín-Morales et al., 2018), and sustainability (Barbalios, Ioannidou, Tzionas, & Paraskeuopoulos, 2013). Finally, the utterly malleable nature of VEs has made them largely studied for the design and testing of simulations in different contexts, such as flight simulators (Amiri Atashgah & Malaek, 2012), emergency and evacuations scenarios (Moussaïd et al., 2016; Schwebel, Severson, & He, 2017; Xi & Smith, 2016), and also for scene rehearsals (Normand et al., 2012).

Among all the application areas explored, from these years onward, a substantial portion of the works covers the educational field, for which a separate sub-category has been identified, which we defined **VEs for Education**. Indeed, in this period, the educational application field has been addressed by many studies from multiple perspectives. As a first matter of investigation, research focused on how to design and implement virtual learning environments (Chow, Herold, Choo, & Chan, 2012; McCaffery, Miller, & Allison, 2011; Smorkalov, Fominykh, & Morozov, 2013), and how their adoption in education can be perceived (Ghanbarzadeh & Ghapanchi, 2020; Kawulich & D'Alba, 2019; Kennedy-Clark, 2011; Marcelino, da Silva, Gruber, & Bilessimo, 2013). Among the most studied factors is how using a VE in the educational sector influences students' learning outcomes (Chau et al., 2013; Nikolaou & Tsolakidis, 2013; Ragan et al., 2010), cognitive abilities (Ragan et al., 2012), and presentation skills (Goldschwendt, Anthes, Schubert, Kranzlmüller, & Petzold, 2014; Van Ginkel et al., 2019). Other studies have combined collaborative VEs with game-based learning, presenting experiences merging the two themes (Berns, Gonzalez-Pardo, & Camacho, 2013; Hassani, Nahvi, & Ahmadi, 2016; Ketelhut & Schifter, 2011). Finally, the remaining studies collected focused on experimenting with VEs to evaluate their impact on specific subjects, such as geometry (Hauptman & Cohen, 2011), mathematics (Bouta, Retalis, & Paraskeva, 2012), and chemistry (Okamoto, Sumida, & Matsubara, 2014).

Interaction and navigation methods & distance and spatial perception. The category, also continuing the trend of the analogous previous category, gathers works that in this decade have investigated the problem of interaction and exploration of VEs, with a particular focus on the theme of "distance perception," which refers to how the distance between virtual elements is perceived and how this influences the interaction experience with them. Many studies have focused on improving the ways of interacting with objects and environments (Argelaguet, Hoyet, Trico, & Lécuyer, 2016; Benzina, Dey, Toennis, & Klinker, 2012; Stenholt & Madsen, 2011), comparing existing techniques (Jang, Vitale, Jyung, & Black, 2017) and proposing frameworks and toolkit for interface design (Frees, 2010) and path planning (Azmandian, Yahata, Bolas, & Suma, 2014). As for VE navigation tasks, these have also been widely studied in recent years. Research has focused mainly on how to simulate natural movements and walking (Matsumoto, Narumi, Ban, Tanikawa, & Hirose, 2017; Pfeiffer, Schmidt, & Renner, 2016; Wendt, Whitton, & Brooks, 2010), how to guide and redirect the user (Guan, You, & Neumann, 2011; Schrom-Feiertag, Settgast, & Seer, 2017; Suma, Bruder, Steinicke, Krum, & Bolas, 2012), and ad hoc interfaces that allow him to control his movement in the most intuitive way possible (R. Tanaka, Narumi, Tanikawa, & Hirose, 2016; Turchet, 2015). As mentioned above, during this decade, the theme of distance perception was largely explored. Extensive studies have been conducted on how this factor is influenced and how it can be manipulated (Ahmed, Cohen, Binder, & Fennema, 2010; Bruder, Steinicke, & Wieland, 2011; Leyrer, Linkenauger, Bülthoff, Kloos, & Mohler, 2011; Suma et al., 2011), comparing the results obtained across different settings and devices (Alexandrova et al., 2010; S.H. Cha, Koo, Kim, & Hong, 2019; Grechkin, Nguyen, Plumert, Cremer, & Kearney, 2010). In addition to visual factors, other elements that could affect it, such as avatars' presence and audio-visual stimuli, have also been analyzed (Phillips, Ries, Kaeding, & Interrante, 2010; Rébillat, Boutillon, Corteel, & Katz, 2012).

Tools & framework for VEs' design & development. The category remains the same as in the previous decade and includes all the works that proposed tools, frameworks, and specific techniques for developing various VEs and their characteristic elements. Research has kept on proposing new tools to assist in creating innovative VEs that could be more efficient (Blom & Beckhaus, 2014; Kalarat, 2014) and dynamic (Blom & Beckhaus, 2014). Some solutions have also been proposed to address the technical challenges, mainly related to the real-time rendering of 3D elements (Ardouin, Lécuyer, Marchal, & Marchand, 2014; Jian, Liao, Fan, & Xue, 2017; Kolic & Mihajlovic, 2012) and scenarios generation (Dema & Sari-Sarraf, 2012; Zook et al., 2012). Moreover, during this decade, the vision of VEs as collaborative virtual spaces was gaining traction; as a consequence, novel architectures were proposed to achieve greater scalability (Lake, Bowman, & Liu, 2010) and integrate cloud and distributed technologies (Krautheim, Phatak, & Sherman, 2010), as well as complete IoT systems exploiting VEs in their software components (Simiscuka & Muntean, 2018; Z. Zhang et al., 2013). The collaborative VEs were also studied to propose ad hoc frameworks (Casarin, Pacqueriaud, & Bechmann, 2018; Perera, Allison, Ajinomoh, & Miller, 2012) to assist their design and development, establishing the trend of multi-user interactive virtual worlds. Lastly, some papers focused on proposing innovative models to approach the design of complex VEs (Chevaillier et al., 2012; López-García, Gallego-Sánchez, Molina-Carmona, & Compañ-Rosique, 2014) and techniques to achieve higher realism and fluidity in the user experience (Caserman, Garcia-Agundez, Konrad, Göbel, & Steinmetz, 2019; Postma & Katz, 2015).

Themes of presence, social interactions, emotions and immersivity. The category encompasses works that have continued to explore the theme of the sense of presence within a VE. Building on the related topics addressed in the previous decade, these years have focused on immersivity and emotionality, as well as social interactions within a VE. On the one hand, works in this category broadly tried to measure what influences immersivity and its impact on the user experience in the VE (Chertoff et al., 2010; Coxon, Kelly, & Page, 2016; Slater, Spanlang, & Corominas, 2010) and how to improve such experience (Brade et al., 2017; Salomoni et al., 2017; Schrom-Feiertag et al., 2017). On the other hand, they studied how immersivity and emotional involvement can be exploited in varied applications, such as educational contexts (Alsina-Jurnet, Gutiérrez-Maldonado, & Rangel-Gómez, 2011; C. Kwon, 2019; Shea & Bidjerano, 2010) and the influence on users' actions and behavior (Lin, Rieser, & Bodenheimer, 2015, 2013; McCreery, Schrader, Krach, & Boone, 2013; Shin, 2018). Furthermore, the works from this decade shown to be highly observant on the themes of social presence and group dynamics in VEs, particularly accentuating the role of avatars and how they influence users' perception of the experience (Fox et al., 2015; Guegan, Buisine, Mantelet, Maranzana, & Segonds, 2016; Hooi & Cho, 2012; Lomanowska & Guitton, 2012; Lortie & Guitton, 2011). Researchers have examined how social dynamics are generated within VEs (Grinberg, Careaga, Mehl, & O'Connor, 2014; Usta, Korkmaz, & Kurt, 2014) and how collaboration between users in cooperative settings can improve (Guitton, 2012; Van Schaik, Martin, & Vallance, 2012). As a final remark for this category, the issue of cybersickness was kept under observation, trying to obtain more insights on how it is generated (Ling, Nefs, Brinkman, Qu, & Heynderickx, 2013; Y. Wang, Chardonnet, & Merienne, 2019).

Metaverse. The category gathers works that specifically address the topic of the metaverse, beginning to materialize the preliminary research of the previous decade. During this decade, seven studies on the topic were identified, laying the groundwork for what would firmly establish itself in the following decade. Among these, some works began exploring the metaverse in collaborative (Yu, Owens, & Khazanchi, 2012) and educational contexts (Getchell, Oliver, Miller, & Allison, 2010; Schaf, Paladini, & Pereira, 2012; Wagner et al., 2013); such areas had already been extensively investigated in VEs and were now being experimented with using this new concept. Similarly, other papers revisited and emphasized categories already present in VEs with early works on the metaverse, such as the design and prototyping of new technologies and methods for its implementation (Cammack, 2010; Fernández-Gallego, Lama, Vidal, Sánchez, & Bugarín, 2010; Schaf et al., 2012). Interestingly, these works are primarily from the first half of the decade, with only one exception (Zhou, Leenders, & Cong, 2018), highlighting the emergence of an interest that only partially materializes during this period.

4.1.4 2020s

The first four years of the 2020s have already provided significant insights into the evolution of research in the context of VEs and the metaverse. Despite covering less than half a decade of research, 102 papers were collected. We clustered such papers into five main categories plus one subcategory, all confirming and evolving the previously addressed themes. What stands out is the substantial increase in papers on the metaverse, which now represents the largest category. Indeed, this recent period marked the most evident shift in interest between the two themes and the emergence of the metaverse as a standalone context. It is also the period during which FACEBOOK rebranded itself as META in 2021 (López-Díez, 2021), bringing the metaverse concept to widespread public attention for the first time. Each paper for each category is shown in Table 4. In this section, we will provide a high-level overview of the collected papers on the metaverse; we will the in-depth thematic analysis discuss in Section 4.2.

Applications of VEs. Increasingly immersive and realistic VEs have made them particularly useful for creating training and simulation environments in various contexts, where ordinary individuals could train in public speaking (Glémarec, Lugrin, Bosser, Buche, & Latoschik, 2022) and professionals could be prepared to manage medical emergencies (Shamir-Inbal, Or-Griff, & Blau, 2023; Vanukuru et al., 2023). On this same line, VEs have been used to train industry operators, simulate working tasks (B. Cha, Bae, Lee, Jeong, & Ryu, 2022; Peruzzini, Grandi, Cavallaro, & Pellicciari, 2021), design and testing of products (Mishra, Abtew, & Bruniaux, 2022), or even the industrial buildings themselves (Podkosova, Reisinger, Kaufmann, & Kovacic, 2022). During this decade, the trend of using VE technology to disseminate culture and social activities has continued through virtual reconstructions of environments (Khundam, 2021; Puig et al., 2020) and interactive group experiences (Baker et al., 2021a). Furthermore, one of the most significant trends remains in the medical and therapeutic fields, particularly in rehabilitation and the recovery of various types of patients. VEs have been used to support cognitive-behavioral therapies for different conditions (García-Batista et al., 2020; González Moraga et al., 2022; Roy et al., 2022; van Veelen et al., 2021), palliative treatments (Eckhoff, Ng, & Cassinelli, 2022) and even innovative interactable VE tools to assist blind users (L. Zhang, Wu, Yang, Tang, & Zhu, 2020).

During this decade, we continued to analyze the subcategory of **VEs for Education**, whose works strictly related to VEs were fewer in number. This is not due to a decline in interest but mostly because education-related work shifted towards the broader concept of the metaverse. In this subcategory, on the one hand, the works concerned the use of new virtual platforms to support and enhance learning activities (Soto, Ocampo, Colon, & Oropesa, 2020; Xing, Huang, Li, & Xie, 2023) and the design of virtual tools able to support individuals with learning difficulties (Jain et al., 2020); on the other hand, researchers have examined the impact of immersive VEs on learning (Jia & Qi, 2023) and students motivation (Ristor, Morélot, Garrigou, & N'Kaoua, 2023), with mostly positive results in both cases.

Interaction and navigation methods & distance and spatial perception. The category includes works that have further explored interaction and exploration within

VEs. This topic has continued to attract interest due to the evolution of technologies and VEs, as well as the ongoing issue of cybersickness. To make movement and the perception of space as realistic as possible, some works have focused on evaluating such aspects by comparing them with the real world (Bhargava et al., 2020; Clemenson, Wang, Mao, Stark, & Stark, 2020) or by varying certain factors within the VE (Halik & Kent, 2021; König et al., 2021; Landeck et al., 2023; Stefanucci et al., 2022). Locomotion techniques have been further studied and improved, testing different controller methods (Caggianese, Capece, Erra, Gallo, & Rinaldi, 2020) and approaches to make the virtual movements more immersive (Choi et al., 2023; S.-U. Kwon et al., 2022), more intuitive (Johanson, Gutwin, & Mandryk, 2023), and reduce the cybersickness (Daşdemir, 2023). Lastly, new user interfaces have been studied to improve the user experience and adapt to emerging technologies (Y. Wang, Hu, & Chen, 2021), along with frameworks for creating innovative interaction systems (M. Huang, Chabot, Krueger, Leitão, & Braasch, 2020).

Tools & framework for VEs' design & development. The category includes recent tools and techniques that support the creation of increasingly extensive and comprehensive VEs, mainly focusing on the automation of this creation and customization. The new tools proposed in the current decade ranged broadly from tools that allowed the creation and specification of 3D virtual elements (L. Zhang & Oney, 2020) to creation tools to enhance users' experience (Avola, Cinque, Foresti, & Marini, 2023). Notably, with the development and spread of innovative and powerful AI technologies, researchers proposed new tools and methods that exploited such technologies to create and customize new VEs automatically (López et al., 2020), even obtaining highly realistic results (Meloni, Pasqualini, Tiezzi, Gori, & Melacci, 2021; Moura, Vieira, & da Silva, 2020). Lastly, improving the 3D rendering results and efficiency was a largely explored theme by works in this category, which focuses on obtaining high levels of realism and accuracy (Bolkas, Chiampi, Chapman, & Pavill, 2020; Li, 2023) and enhancing visualization quality (Y. Kim et al., 2024).

Themes of avatars, self-representation, engagement and immersivity. The category represents an evolution compared to the previous decade: among the works that have focused their research on the theme of virtual presence within a VE, a key element has emerged and become the focus of such studies, namely self-representation in the virtual world, i.e., the user's avatar. Indeed, research has begun to explore the role of this element in the interaction and experience with VEs (Seinfeld, Feuchtner, Maselli, & Müller, 2021) and how its features and implementation can influence aspects of presence (Baker et al., 2021b; Ricca, Chellali, & Otmane, 2020) and social interactions (Freeman, Acena, McNeese, & Schulenberg, 2022; Narayanan, Polys, & Bukvic, 2020; Peña Pérez Negrón, Muñoz, & Lara López, 2020). In addition, the themes that have been extensively investigated in previous decades within this category have also been further explored. Among the most explored ones, the themes of immersivity and presence stood out, with researchers studying how they are affected (Caldas, Sanchez, Mauledoux, Avilés, & Rodriguez-Guerrero, 2022; Weerasinghe et al., 2023) and how they influence factors such as cognitive complexity (Pollard et al., 2020), memory (Cadet & Chainay, 2020), or users intentions and decision making (Oberdörfer, Heidrich, Birnstiel, & Latoschik, 2021; Weller et al., 2022). Further observations have been made on the appearance of VEs and how visual and sensory factors influence user interactions (Schlagowski, Wildgrube, Mertes, George, & André, 2022; Z. Wu et al., 2022; Xia et al., 2023). Lastly, immersivity has also been studied through comparative studies (Brivio et al., 2021; Ritter III & Chambers, 2022) to gather insights on the techniques and methodologies that have yielded the best results in enhancing it, along with the impact of innovative virtual elements (Carnell, Gomes De Siqueira, Miles, & Lok, 2022).

Metaverse. The 2020s saw the emergence and establishment of the metaverse as a fully-fledged topic, initiating its exploration. Such exploration began by defining the foundations of the topic with many general and exploratory works (Babu & Mohan, 2022; Bizel, 2023; Mandala, Jeyarani, Kousalya, Pavithra, & Arumugam, 2023). It then developed into various themes and subcategories, which will analyze the new metaverse theme in similar ways to what happened with the VEs theme. Among these, many works focused on the application of the metaverse in different contexts (Düser et al., 2023; Mancuso, Petruzzelli, & Panniello, 2023; Qayyum et al., 2023), especially education (Fernández-Gallego et al., 2010; Jovanović & Milosavljević, 2022), and tools for its development (Alpala, Quiroga-Parra, Torres, & Peluffo-Ordóñez, 2022; Elhagry, 2023). Indeed, during this decade, the metaverse category became the most populated, with 37 papers. These years also saw the highest number of papers collected overall, highlighting a resurgence in the publication trend coinciding with the appearance of the metaverse. The number and variety of publications on the metaverse during this period allowed us to pinpoint a temporal moment when the metaverse emerged within the long history of VEs, marking the point where the two paths intersected. We will discuss the collected papers for this category in detail in Section 4.2 to address $\mathbf{RQ}_2$.

> ☞ **Answer to $\mathbf{RQ}_1$**
> Research on VEs began in the early 1990s with a few significant works using new specialized tools and technologies. Over the following decades, there was positive growth in the number and variety of publications, culminating in the 2020s. The identified categories remained consistent throughout the history, evolving and innovating. The main research streams were (1) developing new techniques, tools, and frameworks for creating, designing, and enhancing VEs, and (2) applying these VEs in diverse contexts across various research fields. A negative trend appeared toward the end of the 2010s with a decrease in papers but at the start of the 2020s, the trend reversed, registering the highest number of publications and a strong re-emergence of the field. This growth coincides with the emergence of the metaverse as a prominent topic originating from the history of VEs in the early 2020s. While only a few anticipatory papers addressed the topic in previous decades, recent years have seen such an increase that they represent the majority of papers in the decade. Research expanded enough to be analyzed as a distinct trend with its sub-categories, inheriting the historical development of VEs and establishing itself as the new primary trend in research history.

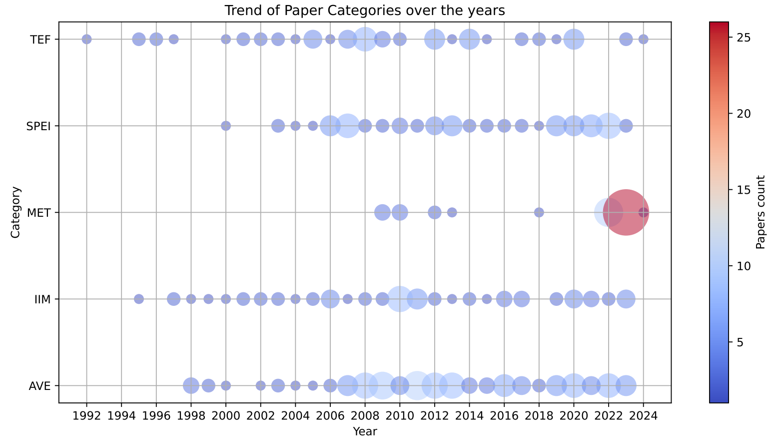


Fig. 8: Bubble chart representing the number of papers published each year for each category. The IDs on the y-axis encode the categories, from top to bottom: Tools & framework for VEs' design & development (TEF), Avatars, self-presence, social interaction & immersivity (SPEI), Metaverse (MET), Interaction & navigation techniques in VEs (IIM), Applications of VEs (AVE).

4.2 $\mathbf{RQ_2}$: On the emergence of the metaverse from the history of VEs

The topic of the metaverse became the most explored theme among the collected papers in the early 2020s, as highlighted in the response to $\mathbf{RQ}_1$. While papers concerning VEs began to experience a downward trend from the second half of the 2010s, publications addressing the metaverse grew rapidly and substantially, with 2022 and 2023 being the years with the highest number of collected papers in the entire historical overview. This remarkable surge in interest is further depicted in Figure 8. Furthermore, Figure 9 shows the number of publications on the metaverse per year and their respective publication venues, confirming the evident explosion of interest in the topic that began in 2022 and solidified in 2023. The figure also reinforces the discussion on venues made for $\mathbf{RQ}_1$ in Section 4.1, highlighting (1) how such venues are highly diverse and (2) the absence of dedicated established venues that treat the metaverse as a primary theme.

We present and discuss the results for $\mathbf{RQ}_2$ by addressing its two components: (1) how the metaverse emerged as a research topic and (2) how it distinguished itself from its shared history with VEs. To achieve this, we selected all the collected papers that addressed the metaverse—those that had been placed in the respective category during the initial analysis—and further analyzed them to obtain a vertical overview of the topic, in contrast to the broader horizontal perspective of the previous $\mathbf{RQ}_1$. Our findings are summarized in Figure 10, which illustrates the points of convergence and divergence between the two topics.

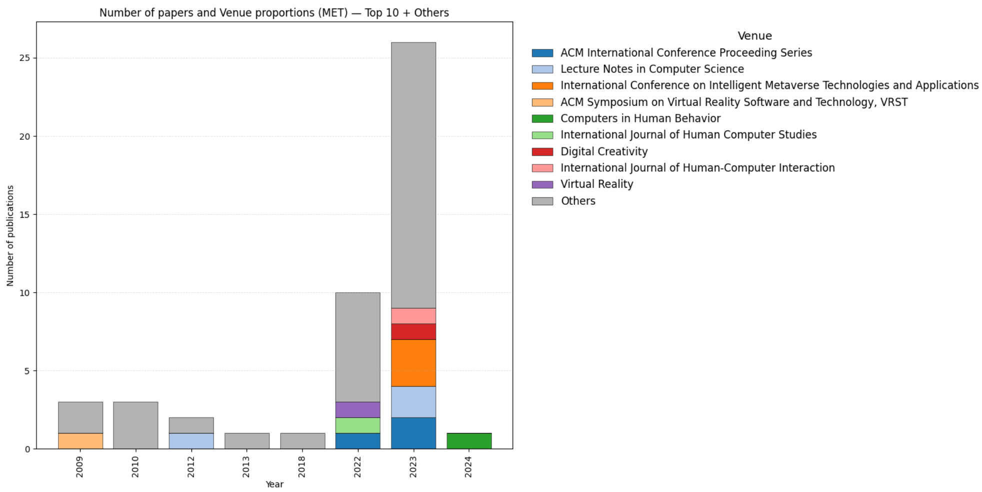


Fig. 9: Publication venues of the metaverse papers grouped by year. The plot shows the Top 10 most frequent venues, the remaining ones have been labeled as “Other”.

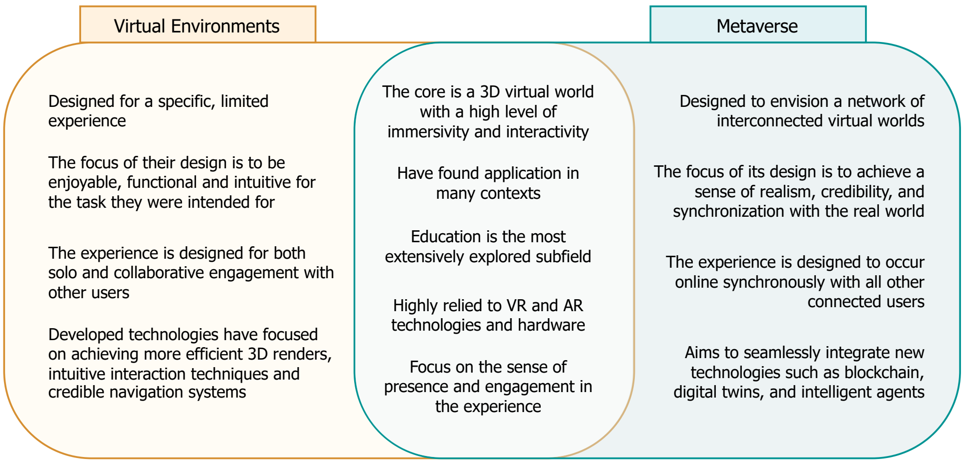


Fig. 10: Venn diagram summarizing the intersections and differences between the two topics identified in the scoping review.

To analyze the emergence of the metaverse as a standalone topic, we pinpointed exploratory and more generic works through which research began to take its initial steps on the topic. Unlike the previous papers on VE, a considerable part of metaverse works aimed to provide the first overviews of the topic and did not fall into any specific subcategory. Such a phenomenon proves that we faced a new research field that required defining its terms, foundations, and key concepts. Exploratory topic analyses have been conducted to gain insights into current and future possibilities (Mandala et al., 2023), its limitations, and under-explored areas (Bizel, 2023). Additionally, online surveys were designed to investigate people's perceptions of the metaverse (Babu & Mohan, 2022). Indeed, works such as the one by Ud Din, Awan, Almogren, and Rodrigues (2023) and the one by Janet et al. (2023) have provided all-around overviews of the evolution of this topic, both from an application perspective and a technical one, with a focus on emerging technologies in this field, such as the blockchain and Non-fungible Tokens (NFTs). Similarly, within such a vast virtual world, researchers have begun to question the definition of fundamental concepts such as the user's digital identity and the associated privacy and security risks (Awadallah, Damiani, Zemerly, & Yeun, 2023). Experiments that utilize the technologies mentioned above have been conducted to ensure these aspects, transitioning from the conceptualization of the metaverse to tangible prototypes that implement the formulated concepts (Gupta, Bhadani, Bandyopadhyay, Banik, & Swain, 2023; Upadhyay, Dantu, He, Badruddoja, & Salau, 2022). Moreover, the explored concepts have also extended to collaborative, work-related, and economic aspects envisioned for the metaverse. Researchers have investigated how immersive metaverse technologies can enhance collaboration among team members (X. Huang & Chen, 2022), identifying key concepts that define a collaborative metaverse, such as avatars, technologies, behaviors, and outcomes (Davis et al., 2009). Finally, dedicated business models have begun to be developed for the metaverse, focusing on concepts of ownership and property rights of digital assets (Zhou et al., 2018). To summarize the extracted information, the acquisition of these papers—the vast majority of which were collected after 2020—evidence the novelty of the metaverse topic and its notable traction in recent years. Although drawing on some characteristics and technologies from the extensively explored field of VEs, the metaverse has been depicted through new terms and fundamental aspects.

Following the identification of works that illustrated the emergence and definition of the metaverse, we were interested in analyzing the remaining papers to gather information on how the topic emerged concerning the broader context of VEs, how it subsequently distinguished itself, and in what ways. To achieve this, we conducted our second thematic analysis on the remaining papers. The results of the analysis identified four categories, which can all be mapped to the themes already observed for VEs but with differences in how these themes were addressed. This strengthens the relationship between the metaverse and VEs, as the former, both temporally and thematically, arises from and evolves what had been explored in the latter. However, within the categories, more specific and recurring elements also emerge, along with dedicated technologies that had not been previously explored, such as the concepts of avatars, digital twins, UGC, and blockchain. Below, we discuss each new category and the papers that belong to them.

Applications of the metaverse. Similarly to what occurred with VEs, from the very early stages of research in this field, the metaverse has begun to be envisioned in various application contexts. Expanding the concept of a virtual world into an interconnected and all-encompassing universe, diverse solutions have been analyzed and proposed for a range of different fields. The most explored areas align with those already tested by VEs, expanding them to encompass the new potential that the metaverse offers. Among them, the metaverse continued the trend in the medical and healthcare fields. Research has begun to propose conceptual models for collaborative metaverse for healthcare teams (Yu et al., 2012) and prototypes to optimize healthcare workflows (Oliveira et al., 2023), along with simulation environments for executing surgeries (Qayyum et al., 2023). Notably, the metaverse explored new trends that diverges from those already studied, which concern business, product engineering, and retail contexts, analyzing new key concepts for integrating the metaverse into these areas (Düser et al., 2023). Ad hoc business models that blend virtual and real environments have been studied and proposed to innovate the business strategies of fashion and retail companies (Mancuso et al., 2023), introducing innovative elements of the metaverse such as avatars and customization (Vyas et al., 2023). Finally, there are also early experiments for more specific application contexts, such as metaverse platforms for hosting graduation events during the COVID-19 pandemic (Gao & Lyu, 2023)and metaverse platforms that model various environments to raise awareness about biodiversity (Johanson et al., 2023).

Metaverse for Education. Education has been the most extensively explored application context, as anticipated in Section 4.1, aligning with the trend of VEs papers. In fact, most of the works that addressed educational themes between 2020 and 2024 shifted their focus from limited VEs to concepts of large, immersive and collaborative metaverse platforms, where various teaching methodologies can be implemented in different disciplines. Exploratory studies have analyzed the literature to begin to outline the foundations of educational metaverse platforms (Bicen & Adedoyin, 2022), identifying their potential and the open challenges (Zonaphan, Northus, Wijaya, Achmad, & Sutoyo, 2022). Alongside this, the prototypes (Jovanović & Milosavljević, 2022) and architectures (Fernández-Gallego et al., 2010) have emerged that implement these concepts, starting to experiment with the impact of the metaverse on teachers and students (Buragohain et al., 2023). The metaverse has begun to be seen as a powerful tool for the education of various disciplines (Schaf et al., 2012), capable of implementing approaches like game-based learning (Getchell et al., 2010) and enhancing aspects of remote teaching (Wagner et al., 2013), which became particularly widespread following the COVID-19 pandemic. Given the nature of the metaverse, the roles of its key elements in education have also been studied. Works in this category further examined and exploited factors that were hinted at in VEs papers, making them the key strengths of the educational metaverse, such as customization, identity exploration, social presence, and the sense of belonging within the educational environment (Garcia, Adao, Pempina, Quejado, & Maranan, 2023; Srivastava, Clemmensen, Yammiyavar, & Badoni, 2023). In addition, various technologies could be leveraged and integrated into the metaverse to enhance the educational experience. These include blending real and virtual elements through VR and AR tools (Al Seiari, Al Kaabi, & Al-Karaki, 2023; T. Kim, Planey, & Lindgren, 2023) and using chatbots that utilize NLP to interact with users (Xie et al., 2023).

Tools & technologies for the metaverse. In line with what was witnessed with the VEs, alongside the emergence of the metaverse as a research area, proposals for tools and frameworks have also been developed to guide its creation and evaluation

(Rajesh, Chinthamu, Rani, Kumar, & Sivaiah, 2023; Richter & Richter, 2023). However, even though the category echoes what was seen with VEs, the way it is explored is what differs the most. If, for VEs, research had focused on tools that assisted in their development, rendering efficiency, and ease of interaction, in the metaverse field varied proposals have explored integrating innovative techniques to make development more automated and accessible and achieve more comprehensive and robust results. In light of this, new themes and technologies that will remain deeply connected to the metaverse are explored, such as UGC, digital twins, and blockchain. **UGC** within metaverse platforms has begun to be recognized as playing a fundamental role in the experience of customization and creation within a metaverse, with works presenting systems for their search and management across different worlds (Eno et al., 2009). **Digital twins**—i.e., the virtual and synchronous representation of a real entity—have been extensively utilized to implement metaverses with seamless communication with the real world, aiding in the creation of realistic replicas of worlds, elements, and avatars (Alpala et al., 2022; Munir et al., 2023). This technology has also shown the ability to leverage techniques like machine learning to quickly and automatically create virtual worlds modeled after real ones (Elhagry, 2023). Similarly, recent **blockchain** technology has been explored to ensure the security and transparency of interactions within the metaverse (Al Shehhi & Otoum, 2023). Indeed, along these same lines, the management of increasingly large and complex architectures has required works that propose ad hoc architectures (Cammack, 2010) and decentralized technologies to ensure security and address identity management and trust issues for users (Mebrahtom, Hadish, Sbhatu, Aloqaily, & Guizani, 2023; Thakur et al., 2023). Finally, chatbots capable of leveraging deep learning techniques have also been integrated into metaverse prototypes to enhance communication between users and the environment (Rajesh et al., 2023).

Themes of engagement and immersivity. This last category encompasses the works that examined the matter of immersivity and engagement in metaverse applications. The themes of engagement and self-representation through avatars, which were numerous in works related to VEs, are less prevalent here. We hypothesize that this is because what was previously analyzed as standalone themes in VEs now constitutes an integral part of the metaverse concept and is addressed more broadly across works in various categories. In this category, we have gathered those studies that focused on engagement and emotional involvement as the main subject of their research. Some studies explored how design elements can evoke real emotions in metaverse participants (Dozio et al., 2022) and what elements in the metaverse can influence users' trust and intentions (L. Zhang, Anjum, & Wang, 2023). Additionally, research looked into how combining the metaverse with AR/VR technologies can enhance users' interaction with the virtual world (Dwivedi et al., 2022). Finally, there were also investigations into potential negative implications of the metaverse, such as escapism in VR experiences (Han, Bergs, & Moorhouse, 2022).

> ☞ **Answer to RQ_2**
> The topic of the metaverse emerged and gained importance in the early 2020s, marked by a significant increase in publications. This rise is evidenced by numerous exploratory

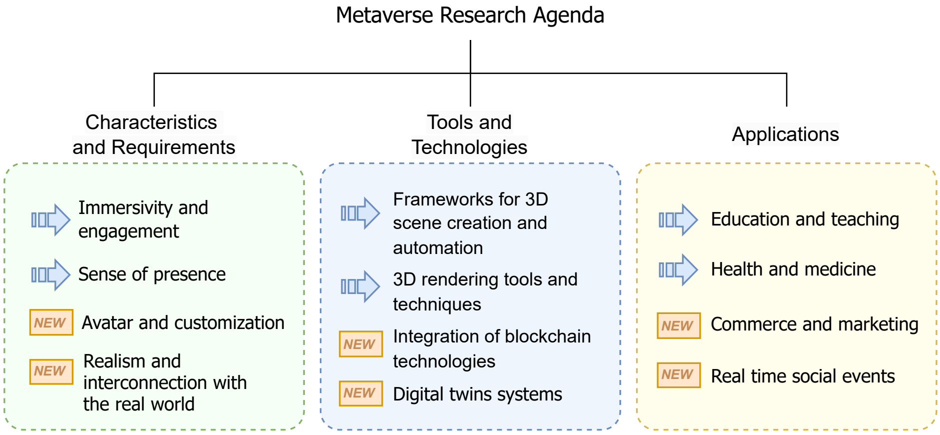


Fig. 11: Summary of the future metaverse research agenda. The entries with the arrow symbol indicate research trends to continue that have already emerged from the history of VEs; the entries marked as *NEW* indicate those that originated with the emergence of the metaverse.

> papers that aimed to provide an overview and define its foundations. Initial efforts focused on establishing a general framework and identifying key characteristics. The metaverse originates from the broader research history of VEs, sharing common features like a 3D virtual world, VR and AR technologies, and experimentation in various contexts. However, thematic analysis revealed that the metaverse distinguished itself for many elements, such as the vision of interconnected virtual worlds, realism, synchronization with the real world, and real-time interaction. It also introduced new aspects like personalization, UGC, and digital twins, which were less emphasized in VE research. Themes of engagement and immersivity, initially explored in VE studies, have been integrated into broader metaverse research, reflecting its more comprehensive nature.

5 Discussion and Future Research Agenda

In this section, we discuss the implications of our research findings on the metaverse research field. We propose a future research agenda that we envision for the topic of the metaverse based on the results of our scoping review and informed by the insights gained from our analysis of the history of VEs and the metaverse. Figure 11 summarizes the structure of the future research agenda, reflecting discussion points that align with the categories of papers identified during the thematic analysis.

Characteristics and Requirements. This point of the agenda is derived from both the category of studies on VEs and the metaverse that explored themes of presence, immersion, and engagement, as well as from the wave of metaverse papers from the early 2020s that focused on its analysis and definition. In light of the results obtained from these papers' analysis, a vision of the metaverse must meet a set of fundamental characteristics and requirements to be defined as such and to distinguish itself from other immersive 3D applications. Such characteristics can be identified by intersecting the elements studied in VEs with the new ones that have emerged from the early studies on the metaverse. Research experimenting with VEs has focused across decades on the theme of presence (Baños et al., 2004; Cadet & Chainay, 2020; Ling et al., 2013) and co-presence with other users (Freeman et al., 2022; Nowak & Biocca, 2003), investigating the factors influencing this perception. This concept has been transferred to the metaverse, where engagement has become a foundational element (Dozio et al., 2022; Dwivedi et al., 2022), as it aims to fully grip the user in interaction with the 3D immersive world. Building on the many results already obtained from past experiments, future research should continue to study this phenomenon in order to enhance and evolve user engagement with new technologies, increasing their sense of presence. In parallel, there are innovative elements already hinted at in previous VE studies but have now become central to the metaverse, namely the role of self-representation within the environment through one's avatar (Davis et al., 2009; Garcia et al., 2023), the possibility of personalizing it and various elements of the experience. In this context, research should start to give these factors a central role, investigating how to implement them and how they influence the overall experience.

> **Toward the Definition of the Metaverse Characteristics and Requirements**
>
> - **Ongoing trends**: investigate factors that influence immersion, engagement, and presence in the metaverse, and explore ways to improve these aspects to create a more seamless and comfortable user experience.
> - **New trends**: study the role of avatars and customization options in the metaverse to enhance users' sense of freedom of expression and representation; investigate the elements that make the metaverse experience more realistic and interconnected with the real world.

Tools and Technologies. This point of the agenda builds on the categories observed in both VEs and the metaverse, which have focused on developing tools and frameworks to support their design and implementation. Research in this direction can continue by consolidating established results and updating them to address new requirements and incorporate recent technological advances. At the same time, the recognition of the metaverse as a distinct concept creates room to refine and extend existing solutions with innovative tools and techniques that facilitate its practical realization. Since both VEs and the metaverse rely on 3D environments, the body of work dedicated to tools for their development and automation (Behmel, Höhl, & Kienzl, 2014; Méndez et al., 2005; Zook et al., 2012) remains highly relevant for metaverse applications. The same applies to research on improving rendering (Ardouin et al., 2014; Kolic & Mihajlovic, 2012), texturing efficiency (Poullis et al., 2008; Smorkalov et al., 2013), and interaction with 3D objects through interfaces and techniques (Frees, 2010; Frees & Kessler, 2005). Further opportunities lie in integrating artificial intelligence for adaptive and automated processes (Gu & Maher, 2005; López et al., 2020), as well as in strengthening data exchange and security frameworks among users (Al Shehhi & Otoum, 2023; Scheffler et al., 2008). With the increasing attention to the metaverse, research directions also need to address its scalability, security, and interoperability with real-world systems. Current developments already new ad-hoc solutions for data management and security in virtual environments (Upadhyay et al., 2022; Weerasinghe et al., 2023) and synchronization with real-world processes (Alpala et al., 2022; Munir et al., 2023). These efforts indicate concrete steps towards integration, while leaving space for the design of additional dedicated technologies (Rajesh et al., 2023; Xie et al., 2023).

> **Toward the Development and Refinement of new ad-hoc Tools and Framework for the Metaverse**
>
> - **Ongoing trends**: refine existing tools and technologies to make the creation of 3D environments increasingly efficient and accessible, as well as improve the efficiency of their rendering across various devices.
> - **New trends**: analyze how to effectively integrate emerging technologies into the metaverse to expand its potential and make it interconnected and interoperable.

Applications. This point of the agenda originates from the category of papers common to both the metaverse and VEs regarding their potential applications in various practical contexts. Both topics have seen numerous experiments on their applicability in entertainment (De Paolis, Aloisio, & Pulimeno, 2009; H. Seo et al., 2000), simulation (Gorman, Singley, & Motai, 2007; Ristor et al., 2023; Schwebel et al., 2017), and even cultural settings (Marín-Morales et al., 2018; Ştefănescu et al., 2008). Among these, the medical and, most notably, the educational contexts have been particularly prominent. These two trends have not been exhausted and are evolving alongside the progress of research in the metaverse context. With the emergence of the metaverse, new possibilities are opening up for the already explored medical and therapeutic simulations with VEs. Research can leverage its real-time collaborative nature to provide increasingly realistic training for various specialized professionals (John, 2008; Shamir-Inbal et al., 2023; Yu et al., 2012) and propose more immersive, high-impact therapies (Avola et al., 2013). Similarly, these potentials can be further exploited in the educational context, continuing the trend of integrating the metaverse with innovative teaching techniques (Bicen & Adedoyin, 2022; Zonaphan et al., 2022). This will allow for overcoming the limitations of physical infrastructures or 2D remote communication platforms (Marcelino et al., 2013). The emerging opportunities involve creating and establishing a fully functioning virtual economy within the metaverse, along with new marketing techniques (Mancuso et al., 2023; Zhou et al., 2018). The metaverse can, in fact, be leveraged in these contexts through new ad-hoc business models that promote the proliferation of commerce and advertising, potentially expanding the operational range of many brands and companies (Vyas et al., 2023). Research should investigate these aspects and propose new methods and frameworks that enable innovative marketing and a novel economy within the metaverse. The social and real-time nature of the metaverse experience is also emerging as a key factor, enabling the organization of large-scale social events with geographically distributed users gathering in the same virtual space (Buthpitiya & Zhang, 2010; Freeman et al., 2022). Research should focus on making these events possible and ensuring a safe and engaging experience, allowing the metaverse to become a space that transcends physical barriers.

> **Toward new Experiments with the Metaverse in various Application Contexts**
>
> - **Ongoing trends**: leverage insights gained from past research to continue studying the applicability of the metaverse in the medical and educational fields, while also implementing new techniques and solutions.
> - **New trends**: analyze the potential of the metaverse to create a virtual economy that supports new forms of marketing, commerce, and real-time social events.

In conclusion, analyzing the entire history of VEs in relation to the metaverse has provided a comprehensive overview of the state-of-the-art for this new topic. The proposed research agenda draws on many of the research trends that have been explored and can be further developed through the new possibilities offered by the metaverse, leveraging the significant years of knowledge already gained on immersive 3D technologies. At the same time, the agenda has highlighted what are the promising new avenues opened by the metaverse, as well as several directions to take in order to achieve a fully realized metaverse that reaches its full potential.

6 Limitations of the Research

We present the potential limitations of our work. A limitation may arise from the decision to rely on a single research database as the source of articles. This choice may have reduced the pool of works considered in the review, limiting it to those available within that database. Since we aimed to cover a broad history connecting two research topics, this decision was necessary to manage the large number of articles we had to consider during the selection phase. Nevertheless, we carefully chose Scopus as our source for two main reasons: (1) it is a comprehensive scientific database that aggregates content from multiple publishers, allowing access to a wide range of works from a single source, and (2) it has broad coverage and provides robust bibliometric tools, which were particularly useful for our objectives.

Another limitation lies in the set of papers collected to trace the history of the two topics. This collection is restricted to the papers selected after the screening phases, thus limiting the results achieved to such a collection. Nevertheless, we adopted a rigorous approach to identify the paper set, relying on the guidelines of Tricco et al. (2018) and enabling us to be confident in the generalizability of our findings.

Lastly, some design choices for the screening phase may have limited the set of selected papers, such as the list of filter keywords that we used to screen abstracts. We attempted to design and fine-tune a comprehensive set of keywords, including the most general terms that papers of interest might contain. This helped us filter out papers captured by the search string that was irrelevant to our research goals. While this approach allowed us to achieve a manageable number of papers, it might have excluded some pertinent works.

7 Conclusion & Future Work

In this work, we conducted a scoping review to analyze the historical development of research in VEs and the metaverse from 1990 to 2024. Our primary goal was to trace the evolution of these interconnected fields, identifying their evolution, their trends, and the emergence of the metaverse as a distinct area of study. We adhered to the PRISMA-ScR guidelines (Tricco et al., 2018) to ensure transparency and completeness in reporting, selecting and reviewing 352 papers from the Scopus database.

We addressed our research questions by reconstructing the historical trajectory of VEs and the metaverse and by identifying the main trends that have shaped their evolution. With respect to $\mathbf{RQ}_1$, our analysis showed how research on VEs, which originated in the early 1990s, grew steadily across decades through two main streams: the development of new techniques, tools, and frameworks, and the application of VEs in diverse domains. Despite a decline in publications toward the end of the 2010s, the field experienced a strong revival in the early 2020s, when the metaverse began to emerge as a distinct research topic, inheriting and extending the legacy of VEs. With respect to $\mathbf{RQ}_2$, we highlighted how the metaverse rapidly gained prominence in the early 2020s, initially through exploratory works aimed at defining its foundations, and then by distinguishing itself with features such as interconnected virtual worlds, synchronization with the real world, and customization. While maintaining continuity with VEs in terms of immersive 3D VEs and engagement, the metaverse consolidated these aspects into a broader research agenda, marking a clear evolution of the field.

The contribution our work brings to the scientific community is twofold. First, it consolidates a fragmented body of knowledge into a common foundation that allows the two broad topics under analysis to be understood as part of a single historical trajectory. Second, it outlines a research agenda that builds directly on the historical examination we conducted, helping to define potential future directions by drawing on past developments and highlighting emerging opportunities. By building on our results and from the new structured knowledge base, we envision our work to serve as a reference point for researchers approaching the field, and practitioners who need a historically grounded view to inform future developments and decisions.

We expect our work to enable many future research studies. Future work can build on our results not only to extend and refine the findings we have mapped, but also to generate new insights that respond to the rapidly evolving nature of the field. Indeed, given the speed and intensity of recent publications, our results can be continuously integrated with new studies to validate, challenge, or expand the trends we identified. Moreover, future research can also build directly on the agenda we have outlined, which we intentionally framed as a roadmap that researchers can use as starting points for both empirical investigations and conceptual advancements. This means that each of the key areas identified can now serve as a basis for targeted research and experimental studies.

Declarations

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval. Not applicable.

Data availability. The authors have made the replication package of the scoping review available in their public online appendix (Pentangelo et al., 2024).

Appendix A: Tables of Paper Categories for each Decade

□ Applications of VEs	Yura et al. (1998), Krapichler et al. (1998), Purschke et al. (1998), Tomek and Giles (1999), Wilson (1999)
□ Interfaces and interaction methods	S.E. Chen (1995), Coninx et al. (1997), Mine et al. (1997), Hendrix and Barfield (1995), Usoh et al. (1999)
□ Generation and rendering algorithm	Cruz-Neira et al. (1992); Matos et al. (1997); Nishino et al. (1996); Pausch et al. (1995); Thalmann et al. (1996); Zilles and Salisbury (1995)

Table 1: Paper Categories from 1990 to 1999

□ Applications of VEs	H. Seo et al. (2000), Schnabel (2002), Hoffman et al. (2003), J.X. Chen et al. (2003), Q. Wang and Li (2004), Johnsen et al. (2005), Cao et al. (2006), Richard, Tijou, Richard, and Ferrier (2006), Depradine (2007), Di Blas and Poggi (2007), de Haan et al. (2007), Gorman et al. (2007), Bridge et al. (2007), John (2008), Kock (2008), Limniou, Roberts, and Papadopoulos (2008), Lang, MacIntyre, and Zugaza (2008), Salzmann and Froehlich (2008), Ştefănescu et al. (2008), Bossard, Kermarrec, Buche, and Tisseau (2008), Schwebel, Gaines, and Severson (2008), De Paolis et al. (2009), Attasiriluk et al. (2009), Aguayo (2009), De Lucia et al. (2009), Dalgarno, Bishop, Adlong, and Bedgood Jr (2009), Jamaludin, San Chee, and Ho (2009), De Amicis et al. (2009), De Freitas and Neumann (2009), Smith and Ericson (2009)
□ Interaction techniques for VEs	Hindmarsh et al. (2000), Willans and Harrison (2001), Jack et al. (2001), J. Lee et al. (2002), Jansen-Osmann (2002), Lok et al. (2003), Chua et al. (2003), Barrera et al. (2004), Frees and Kessler (2005), Schoenfelder and Spenling (2005), J. Yoon and Ryu (2006), J.S. Yoon and Maher (2005), Tan et al. (2006), Steed (2006), Interrante et al. (2007), Lahav et al. (2008), Lahav and Mioduser (2008), Liu et al. (2009), Ruddle and Lessels (2009)
□ Tools & framework for VEs' design & development	Shum and Szeliski (2000), B. Huang et al. (2001), Taylor et al. (2001), Crosier et al. (2002), G.A. Lee et al. (2002), Bowman et al. (2003), Linebarger et al. (2003), J. Seo and Kim (2004), Gu and Maher (2005), Menchaca et al. (2005), Méndez et al. (2005), Mendez and De Antonio (2005), Andujar et al. (2006), Antonya and Talaba (2007), Ieronutti and Chittaro (2007), Rueda et al. (2007), Zeng and Tan (2007), Liang et al. (2008), Trenholme and Smith (2008), Gerbaud, Mollet, Ganier, Arnaldi, and Tisseau (2008), Kurillo et al. (2008), Scheffler et al. (2008), Poullis et al. (2008), Barsoum and Kuester (2008), Boukerche et al. (2009), Oyarzun et al. (2009), Ingrassia and Cappello (2009)
□ Sense of self-presence, co-presence, emotions and immersivity themes	Nichols et al. (2000), Meehan et al. (2003), Nowak and Biocca (2003), Baños et al. (2004), Heldal et al. (2005), Young et al. (2006), Interrante et al. (2006), Ries et al. (2006), Narayan et al. (2005), Parsons et al. (2006), Riva et al. (2007), Interrante et al. (2008), Burns et al. (2007), Fink et al. (2007), Luo et al. (2007), Tortell et al. (2007), Bailenson et al. (2007), Takatalo et al. (2008), Bormann (2008), Ries, Interrante, Kaeding, and Phillips (2009), Steinicke, Bruder, Hinrichs, Steed, and Gerlach (2009)
□ Metaverse	Davis et al. (2009), Sébastien et al. (2009), Eno et al. (2009)

Table 2: Paper Categories from 2000 to 2009

Applications of VEs	Buthpitiya and Zhang (2010), Hongmin et al. (2010), Ranky et al. (2010), Guidali et al. (2011), Harter, Lu, Kotturu, and Pierce (2011), Lai et al. (2011), Aleotti and Caselli (2011), Maciel et al. (2011), Feasel et al. (2011), Amiri Atashgah and Malaek (2012), Camus et al. (2012), Normand et al. (2012), Alvarez and Su (2012), Barbalios et al. (2013), Bhagwatwar, Massey, and Dennis (2013), Avola et al. (2013), Sharma and Schroeder (2013), H.Y. Lee and Lee (2014), Goldschwendt et al. (2014), Puthenveetil et al. (2015), Lahav et al. (2015), Vosniakos and Gogouvitis (2015), Carvalho et al. (2016), Moussaïd et al. (2016), Damiano and Lombardo (2016), de Oliveira et al. (2016), Xi and Smith (2016), Lopez and Tucker (2017), E.H. Tanaka et al. (2017), Schwebel et al. (2017), Vonach, Gatterer, and Kaufmann (2017), Cavalcante et al. (2018), Marín-Morales et al. (2018), Gulec et al. (2019), Doumanis et al. (2019)
VEs for Education	Ragan et al. (2010), McCaffery et al. (2011), Kennedy-Clark (2011), Ketelhut and Schifter (2011), Hauptman and Cohen (2011), Chow et al. (2012), Marcelino et al. (2013), Ragan et al. (2012), Bouta et al. (2012), Berns et al. (2013), Smorkalov et al. (2013), Nikolaou and Tsolakidis (2013), Chau et al. (2013), Okamoto et al. (2014), Hassani et al. (2016), Ghanbarzadeh and Ghapanchi (2020), Van Ginkel et al. (2019), Kawulich and D'Alba (2019)
Interaction and navigation methods & distance and spatial perception	Phillips et al. (2010), Bach and Scapin (2010), Frees (2010), Alexandrova et al. (2010), Wendt et al. (2010), Grechkin et al. (2010), Ahmed et al. (2010), Ren, Yeh, and Lin (2010), Suma et al. (2011), Guan et al. (2011), Bruder et al. (2011), Stenholt and Madsen (2011), Leyrer et al. (2011), Suma et al. (2012), Rébillat et al. (2012), Benzina et al. (2012), Azmandian et al. (2014), Ponto, Chen, Tredinnick, and Radwin (2014), Turchet (2015), Pfeiffer et al. (2016), R. Tanaka et al. (2016), Argelaguet et al. (2016), Jang et al. (2017), Schrom-Feiertag et al. (2017), Matsumoto et al. (2017), S.H. Cha et al. (2019), Hadnett-Hunter, Nicolaou, O'Neill, and Proulx (2019)
Tools & framework for VEs' design & development	Lake et al. (2010), Krautheim et al. (2010), Dema and Sari-Sarraf (2012), Zook et al. (2012), Kolic and Mihajlovic (2012), Perera et al. (2012), Chevaillier et al. (2012), Z. Zhang et al. (2013), López-García et al. (2014), Behmel et al. (2014), Kalarat (2014), Ardouin et al. (2014), Blom and Beckhaus (2014), Postma and Katz (2015), Jian et al. (2017), Smolentsev, Cornick, and Blascovich (2017), Simiscuka and Muntean (2018), Casarin et al. (2018), Caserman et al. (2019)
Themes of presence, social interactions, emotions and immersivity	Shea and Bidjerano (2010), Slater et al. (2010), Chertoff et al. (2010), Lortie and Guitton (2011), Alsina-Jurnet et al. (2011), Hooi and Cho (2012), Van Schaik et al. (2012), Lomanowska and Guitton (2012), Guitton (2012), McCreery et al. (2013), Chellali, Milleville-Pennel, and Dumas (2013), Lin et al. (2013), Fox, Bailenson, and Tricase (2013), Ling et al. (2013), Grinberg et al. (2014), Usta et al. (2014), Lin et al. (2015), Fox et al. (2015), Guegan et al. (2016), Coxon et al. (2016), Brade et al. (2017), Salomoni et al. (2017), Shin (2018), Nelson and Guegan (2019), Guo et al. (2019), Simon and Greitemeyer (2019), C. Kwon (2019), Y. Wang et al. (2019)
Metaverse	Cammack (2010), Getchell et al. (2010), Fernández-Gallego et al. (2010), Schaf et al. (2012), Yu et al. (2012), Wagner et al. (2013), Zhou et al. (2018)

Table 3: Paper Categories from 2010 to 2019

Applications of VEs	Macías García, Cortés Pérez, and Izaguirre Alegría (2020), García-Batista et al. (2020), L. Zhang et al. (2020), Puig et al. (2020), Baker et al. (2021a), Khundam (2021), van Veelen et al. (2021), Peruzzini et al. (2021), Podkosova et al. (2022), Glémarec et al. (2022), Mishra et al. (2022), B. Cha et al. (2022), González Moraga et al. (2022), Roy et al. (2022), Eckhoff et al. (2022), Vanukuru et al. (2023), Shamir-Inbal et al. (2023)
VEs for Education	Zucchi, Füchter, Salazar, and Alexander (2020), Soto et al. (2020), Jain et al. (2020), Behmel et al. (2014), Li (2023), Ristor et al. (2023)
Interaction and navigation methods & distance and spatial perception	Clemenson et al. (2020), Caggianese et al. (2020), M. Huang et al. (2020), Bhargava et al. (2020), Y. Wang et al. (2021), König et al. (2021), Halik and Kent (2021), Stefanucci et al. (2022), S.-U. Kwon et al. (2022), Daşdemir (2023), Landeck et al. (2023), Choi et al. (2023), Johanson et al. (2023)
Tools & framework for VEs' design & development	Bolkas et al. (2020), López et al. (2020), L. Zhang and Oney (2020), Meloni et al. (2021), Moura et al. (2020), Avola et al. (2023), Li (2023), Y. Kim et al. (2024)
Themes of avatars, self-representation, engagement and immersivity	Peña Pérez Negrón et al. (2020), Narayanan et al. (2020), Ricca et al. (2020), Pollard et al. (2020), Cadet and Chainay (2020), Oberdörfer et al. (2021), Baker et al. (2021b), Seinfeld et al. (2021), Garcia-Hernandez, Guzman-Alvarado, and Parra-Vega (2021), Brivio et al. (2021), Khojasteh and Won (2021), Weller et al. (2022), Z. Wu et al. (2022), Schlagowski et al. (2022), Carnell et al. (2022), Caldas et al. (2022), Zaman, Koo, Abbasi, Raza, and Qureshi (2022), Ritter III and Chambers (2022), Freeman et al. (2022), Weerasinghe et al. (2023), Xia et al. (2023)
Metaverse	Dozio et al. (2022), X. Huang and Chen (2022), Upadhyay et al. (2022), Bicen and Adedoyin (2022), Babu and Mohan (2022), Zonaphan et al. (2022), Dwivedi et al. (2022), Alpala et al. (2022), Han et al. (2022), Jovanović and Milosavljević (2022), Bizel (2023), Thakur et al. (2023), Mandala et al. (2023), Buragohain et al. (2023), Düser et al. (2023), Qayyum et al. (2023), Munir et al. (2023), Xie et al. (2023), Rajesh et al. (2023), Mancuso et al. (2023), Al Seiari et al. (2023), Awadallah et al. (2023), Gupta et al. (2023), Ud Din et al. (2023), Janet et al. (2023), Garcia et al. (2023), Oliveira et al. (2023), Al Shehhi and Otoum (2023), Gao and Lyu (2023), Elhagry (2023), L. Zhang et al. (2023), T. Kim et al. (2023), Vyas et al. (2023), Mebrahtom et al. (2023), Srivastava et al. (2023), Richter and Richter (2023), Maden and Yücenur (2024)

Table 4: Paper Categories from 2020 to 2024

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