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Publication performance and trends in virtual reality research in education fields: a bibliometric analysis

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Abstract
Virtual Reality (VR) technology has the potential to enhance education by providing immersive and engaging learning experiences that can improve teaching and learning outcomes. While there is a growing interest in utilizing VR in education settings, further research is needed to understand its pedagogical effectiveness and address associated considerations and challenges. This bibliometric study comprehensively analyzes 1,157 relevant articles from the Social Science Citation Index (SSCI) and the Science Citation Index Expanded (SCI-EPANDED) to gain insights into the current state of VR integration in education. The analysis revealed variation in VR adoption and research output across countries and institutions, underscoring the importance of collaboration and knowledge-sharing in the field. Key research areas and trends, such as the use of VR for skill development and training, were identified. Additionally, the study highlighted the need for more research on the pedagogical effectiveness of VR. The findings carry practical implications for guiding future research shaping policy decisions and advocating for a concerted effort to harness VR's capabilities in education. This study serves as a practical roadmap, promoting the implementation and improvement of VR technology and fostering equitable and inclusive educational practices.

Keywords Augmented and virtual reality · Pedagogical issues · Distance education and online learning · Cooperative/collaborative learning · Improving classroom teaching

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1 Introduction

Virtual Reality (VR) is a technology that creates a computer-generated, three-dimensional simulation of an environment that can be interacted with in a seemingly real or physical way, using special electronic equipment such as a helmet or gloves [1]. The concept of VR is not new, with the first recorded implementation of a digital VR system dating back to 1966 in the form of a flight simulator designed for training purposes for the US Air Force [2]. VR has evolved and can be categorized into two types: non-immersive VR, which can simulate real or imagined places, and immersive VR, which provides the perception of being physically present in a non-physical world [3]. VR technology is becoming more and more popular worldwide in a variety of industries [4], including education, as it develops and becomes more affordable [5]. Immersion VR versions of educational tools that were previously created for desktop or mobile devices have gradually been modified and now necessitate the use of head-mounted displays. The fundamental assumption is that this greater immersion will enhance the learning process and raise student motivation [6].

VR offers advantages in teaching historical knowledge and medieval urban layout, including enhanced immersion [7, 8], increased student participation and involvement [9], and the ability to explore virtual reconstructions of historical sites [10]. A study conducted by Checa and Bustillo [11] has further confirmed these advantages and identified the following disadvantages technical challenges such as motion sickness in VR [12], determining effective educational strategies [3], and limitations of 3D models [13] need to be addressed for successful implementation. Further research is necessary to optimize the use of VR in education [14], considering both its benefits and limitations [6].

Traditional teaching and learning approaches are no longer effective in fulfilling learners' expectations [15, 16]. VR has emerged as a game-changing technology in the realm of education, offering a multitude of advantages and prospects. The immersive nature of VR provides more effective engagement and significantly improved knowledge retention in education [17]. Additionally, it provides students with a genuine and controlled learning environment in which they can practice skills and apply information through the creation of realistic simulations of situations [18]. VR platforms serve as a bridge across geographical divides, facilitating remote learning, a role that has been particularly crucial during the COVID-19 pandemic [19]. Despite numerous positive findings on the use of VR in education, VR systems have failed to gain widespread adoption in education [20]. Nonetheless, VR technology has advanced to a degree where it is not only conceptually valuable but also has evident practical application in educational settings.

The field of education has been slow to adopt technology changes in the past, but VR technology has begun to transition from a fringe technology to a mainstream technology capable of being used in educational practice [21]. Overall, VR may fill a niche in current educational technologies and become a key player in a post-device era [22]. Nevertheless, there remain significant factors and obstacles that are specific to VR technology, which educators must confront, such as surpassing the initial high levels of student engagement and motivation, and instead emphasizing the pedagogical approaches and experiences that VR enables [23]. Additionally, the potential sanitation concerns associated with classroom sets of VR headsets may render them obsolete [22].

VR technology has gained significant attention in education due to its potential to enhance engagement, knowledge retention, and practical skills development. However, there is a need for a comprehensive understanding of the current research landscape in VR within the field of education. This study aims to bridge this research gap by conducting a

bibliometric analysis to explore trends, research themes, challenges, and future directions in VR-based education. By addressing these factors, the study aims to contribute to the scientific community's understanding of the impact of VR on education and provide valuable insights for future research and informed policy decisions in integrating VR technology into educational settings.

So far, some review studies have been conducted to explore different aspects of VR in education. For instance, Marougkas et al. [24] conducted a review study to investigate educational theories and methodologies related to the utilization of VR systems in educational and tutoring contexts. Rojas-Sánchez et al. [25] performed a review and bibliometric analysis on VR in education. Marougkas et al. [26] highlighted personalization strategies used in immersive VR for educational purposes. Radianti et al. [27] centered on examining the existing structure of the domain, encompassing learning content, VR design components, and learning theories.

However, a bibliographic study focused on VR in education is essential for gaining comprehensive insights into the current research landscape within this dynamic field. As VR is a rapidly evolving field, a bibliographic study helps stakeholders stay updated on the latest technological developments, contributing to informed and effective implementation strategies in educational settings. This bibliometric study aims to explore and assess the current state of research on VR within the field of education to address the following research questions:

RQ1: What trends in publication performance, including publication growth, citation impact, and collaboration networks, can be identified in the field of VR in education, and how have these trends evolved?

RQ2: What are the predominant research themes and areas of focus within the realm of VR in education?

RQ3: What are the primary challenges and directions that have been documented in the literature regarding the use of VR in education, and how have researchers and educators addressed these challenges or proposed future directions?

By bridging this research gap, the study aims to provide a valuable contribution to the scientific community. Through the synthesis and analysis of available literature, valuable insights into the current state of bibliometric research on VR will be provided. Additionally, this study will identify key research areas and trends, providing directions for future avenues of research and informing policy decisions regarding the integration of VR technology into educational settings. Ultimately, this study aims to foster a deeper understanding of the substantial impact of VR on education and contribute to progress in this area.

In the following sections, this paper is structured as follows. Section 2 presents the methodology employed to conduct the bibliometric analysis. Section 3 presents the findings related to each RQ. Section 4 provides discussions, highlighting the trends, research themes, challenges, and future directions identified in the literature related to VR in education. Section 5 provides conclusions and implications for further research and policy decisions.

2 Method

The phrase "bibliometric analysis," used in this study was first introduced in 1969 by Pritchard. A method known as "bibliometric analysis" attempts to quantify, track, and evaluate scientific literature by taking into account the publications of authors, the most

prestigious journals, techniques, and the outcomes achieved [28]. According to Ellegaard, O., & Wallin, J. A. (2015), "bibliometric methods" or ''analysis'' are now significantly determined as scientific specialties and are considered as a fundamental aspect of research assessment methodology notably within the applied and scientific fields. This method has been successfully used in different contexts such as education [29]. In bibliometric analysis, patterns and trends in published literature is examined using statistical techniques. Examples of these patterns and trends include the frequency of a certain term, the number of citations an article receives, and the distribution of research themes over time.

As explained by Donthu, N et al. (2021), the bibliometric analysis methods are divided into two groups "performance analysis" and "science mapping". Performance analysis focuses on of research contributions. This study conducted performance analysis by covering publication-related metrics, citation-related metrics, and citation and publication-related metrics. While our bibliometric analysis focuses on existing publications up until May 2023, we acknowledge the importance of discussing recent studies on VR in education to situate our findings within the context of the most current scholarship.

Figure 1 illustrates the steps followed in this study. Data for this study were collected on May 2023, by extracting information from the Social Science Citation Index (SSCI) and Science Citation Index Expanded (SCI-EXPANDED) online databases. To provide insights into the latest developments in VR research within the education field, we supplement our analysis by including a subsection (discussion of recent studies) in the Findings and Discussion section that highlights and discusses recent studies. Although these recent studies will not be included in this study, their inclusion in our discussion will help us address the current state of research and its implications for VR in education.

According to the latest Journal Citation Reports (JCR) released by Clarivate on June 30, 2022, there is a total of 9,649 journals categorized under 178 Web of Science categories in SCI-EXPANDED, while SSCI includes 3,568 journals across 58 Web of Science categories. Within these journals, 381 were classified under education-related categories, including education and educational research (270 journals in SSCI), educational psychology (61 journals in SSCI), special education (44 journals in SSCI), and scientific disciplines education (44 journals in SCI-EXPANDED).

To ensure thorough search coverage, we employed the use of quotation marks "" and the Boolean operation OR to guarantee the inclusion of at least one search keyword in the topic field (title, abstract, author keywords, and keywords plus) from 1993 to 2022. Our search specifically targeted the keywords "virtual reality." To maintain analysis accuracy, we also included fewer common terms like "virtual realities," "realities of virtual," and "reality of virtual," as well as terms with missed spaces such as "virtual realitywere," in both the SSCI and SCI-EXPANDED databases.

Therefore, a total of 1,411 documents were searched from 1993 to 2022. The comprehensive literature records of SSCI and SCI-EXPANDED, along with the corresponding citation. The counts for each year have been downloaded into Microsoft Excel (365). Manual coding was carried out to further improve the data analysis process [30, 31]. Journal impact factors (IF_{2021}) were acquired from the 2021 edition of the Journal Citation Reports (JCR).

To improve the search strategy of the Topic (TS) bibliometric study in the Web of Science Core Collection, the "front page" filter including the title, the abstract, and the author keywords (Fu et al., 2012) has proven effective in a wide range of SSCI journals, including the *International Review of Economics and Finance* (Ho, 2021a), the *International*

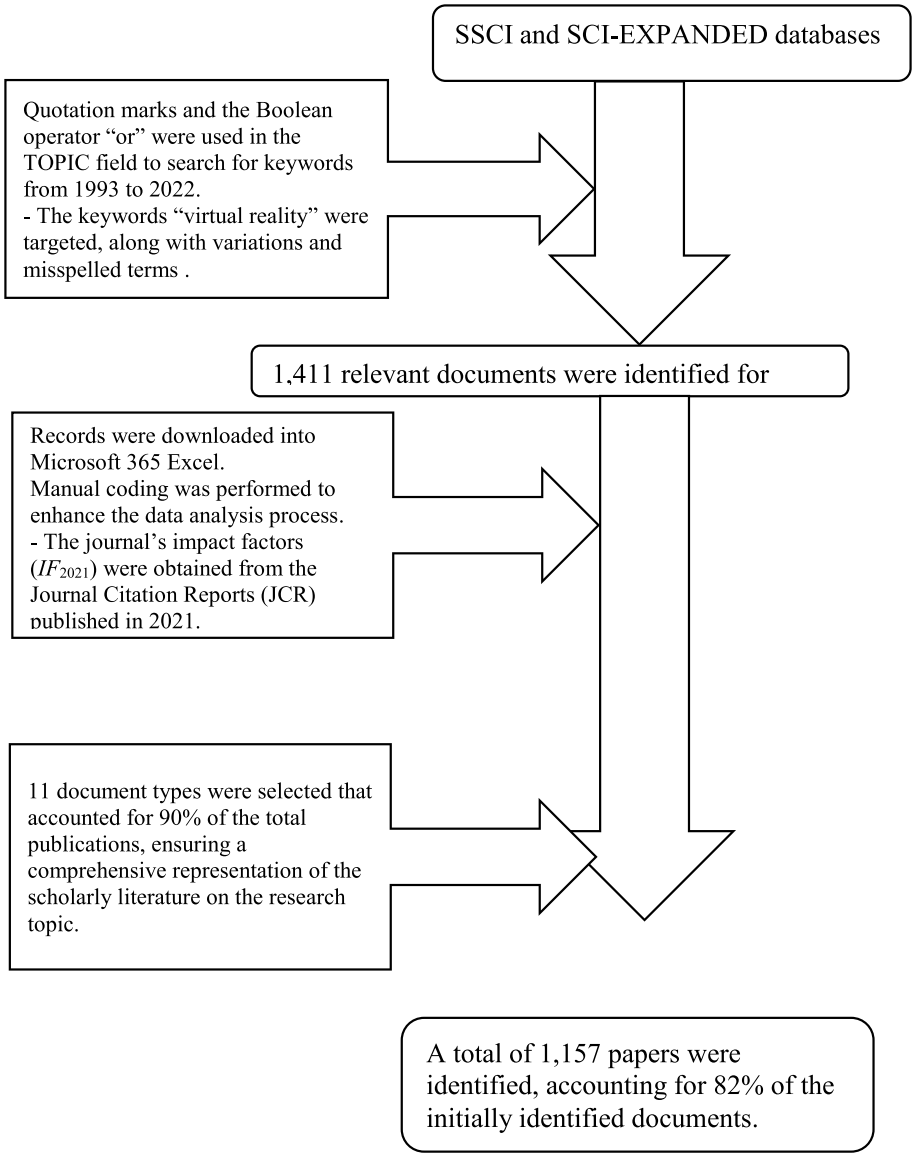

Fig. 1 Method steps and analysis process

Journal of Health Planning and Management (Ho, 2021b), and *European Planning Studies* (Ho, 2019). Searching for documents containing the search keywords specified on their "front page" yielded a total of 1,157 documents, or 82% of the 1,411 documents initially identified. The search was conducted in the education-related categories of SSCI and SCI-EXPANDED, spanning the years 1993 to 2022. It should be noted that all citations from the original text have been preserved in this revised version.

To obtain more precise and accurate results in the analysis of scientific research, this study incorporated additional categorization based on corresponding authors, institutions, and countries. While the SSCI and SCI-EXPANDED databases designate the author as the corresponding author, in this study, we opted to use the term "corresponding author" instead. For unidentified articles in the Web of Science Core Collection, a single author was identified as both the first author and corresponding author. Similarly, the first author institution and country were classified as the corresponding author institution and country, respectively, in articles with a single institution or country. In instances where articles had more than one corresponding author. All corresponding authors, institutions, and countries were considered separately. Additionally, articles with corresponding authors listed in both the SSCI and SCI-EXPANDED databases were examined, with a focus on those with address-only information. These articles were reviewed, and the addresses were replaced with affiliation names, as described in a study by Al-Moraissi et al. [30]. Finally, affiliations from England, Scotland, North Ireland (Northern Ireland), and Wales were reclassified as being from the United Kingdom (UK) [32]. All citations used in the original text have been retained in this modified version. By incorporating a subsection discussing recent studies, we ensure that our findings are situated within the context of the most current scholarship, providing a comprehensive analysis of VR research in education.

The evaluation of publications was carried out using different citation indicators, including:

C_{year}: number of citations received from the Web of Science Core Collection in a specific year (e.g., C_{2022}: means the number of citations for 2022, as proposed by Ho [33].
TC_{year}: the total number of citations received from the Web of Science Core Collection from the year of publication to the end of the most recent year (2022 in this study; TC_{2022}) as introduced by [34].
CPP_{year}: the average number of citations per publication ($CPP_{2022} = TC_{2022}/TP$), where TP denotes the total number of publications, as suggested by Ho [35].

Six publication indicators were used to assess the publication performance of countries and institutions, as proposed by Hsu and Ho [36]:

TP: total number of articles.
IP: number of articles published by a single country or institution (IP_C or IP_I, respectively).
CP: number of internationally collaborative articles or inter-institutionally collaborative articles (CP_C or CP_I, respectively).
FP: number of articles by the first author.
RP: number of articles by corresponding authors.
SP: number of single-authored articles.

Additionally, six citation indicators (CPP_{2022}) linked to the six publication indicators were used to assess the impact of publications on countries and institutions, as proposed by Ho and Mukul [37].

3 Findings and discussion

3.1 RQ1: Evolution of publication performance: Trends in VR in education

3.1.1 Characteristics of document types

The research topic's document type characteristics were analyzed based on their average number of citations per publication ($CPP_{year} = TC_{year}/TP$) and the average number of authors per publication ($APP = AU/TP$), as proposed by Monge-Nájera and Ho [38]. The use of TC_{2022} and CPP_{2022} was advantageous due to their consistency and ensured repeatability, as compared to the number of citations from the Web of Science Core Collection directly [39].

A total of 1,157 documents were identified among 11 document types in the four education-related categories in SSCI and SCI-EXPANDED from 1993 to 2022, as detailed in Table 1. This publication count included 1,047 articles, which accounted for 90% of the total documents and had an *APP* of 3.9 authors.

Proceedings papers had the highest CPP_{2022} value among all document types, with 46 citations, while reviews had a CPP_{2022} value 1.6 times higher than that of articles. Although this value was lower than some topics published in SSCI and SCI-EXPANDED, such as wound dressing (3.0 times), total quality management (3.3 times) [40], and metal–organic framework (5.5 times) [41], it exhibited a higher value compared to other topics, for instance, fracture nonunion (1.3 times) and breast reconstruction (0.86 times) [42].

A total of 70 reviews were published in 34 journals, with *Nurse Education Today* with an IF_{2021} of 3.906 (9 reviews; 13% of 70 reviews), *Computers & Education* with an IF_{2021} of 11.182 (8; 11%), and *Journal of Surgical Education* with an IF_{2021} of 3.524 (6; 8.6%) being the top three journals based on the number of reviews published. Among the articles, English was the most commonly used language, with 99% (1,036 of 1,047) of the articles being written in English. The remaining articles were written in Spanish (5 articles), Russian (3), German (2), and Portuguese (1).

Table 1 Citations and authors according to the document type

Document type	*TP*	%	*AU*	*APP*	TC_{2022}	CPP_{2022}
Article	1,047	90	4,127	3.9	29,320	28
Review	70	6.1	255	3.6	3,053	44
Proceedings paper	22	1.9	68	3.1	1,005	46
Book chapter	14	1.2	38	2.7	92	6.6
Editorial material	13	1.1	40	3.1	144	11
Meeting abstract	8	0.69	24	3.0	0	0
Letter	6	0.52	21	3.5	11	1.8
Book review	5	0.43	5	1.0	1	0.20
News item	4	0.35	16	4.0	8	2.0
Correction	3	0.26	9	3.0	0	0
Reprint	1	0.086	2	2.0	3	3.0

TP: total number of publications; *AU*: number of authors; *APP*: average number of authors per publication; TC_{2022}: total number of citations from the Web of Science Core Collection received since the publication until the end of 2022; CPP_{2022}: average number of citations per publication (TC_{2022}/TP)

It is worth noting that some documents in the Web of Science Core Collection could be categorized into two document types. Such as 22 proceedings papers and 133 book chapters were also classified as articles. Therefore, the cumulative percentage exceeded 100% in Table 1 [43]. The contributions of various document types were different, with articles being the most commonly used document type in the research topic (introduction, method, results, discussion, and conclusion). Hence, they were chosen for further analysis [37].

In conclusion, the proposed characteristic of document types based on the average number of citations per publication (CPP_{year}) and average number of authors per publication (APP) offers valuable insights into the research output in the education field. The study revealed that out of the 1,157 education-related documents analyzed, articles were the most prevalent document type, accounting for 90% of the total with an APP of 3.9 authors. Proceedings papers had the highest CPP_{2022} value of 46, while reviews had a CPP_{2022} value of 1.6 times that of articles. These results could help researchers' select pertinent and impactful literature in the education field and emphasize the need for further investigation into the influence of language on output dissemination.

3.1.2 Characteristics of publication results

To gain important insights into development trends and publication impact, Ho [35] established a link between the annual number of publications (TP) and their average number of citations per publication (CPP_{year}) annually. Over the past ten years, this methodology has been widely applied in a variety of scientific fields, including studies of metal–organic systems [41], breast reconstruction [42], and fracture nonunion [44].

Figure 2 illustrates the temporal distribution of the annual number of articles and their CPP_{2022}. The count of articles pertaining to VR in education-related fields exhibited a gradual growth from three articles in 1993 to nine articles in 2006, followed by a moderate increase over the subsequent decade. However, in recent years, there has been a remarkable surge, with the number skyrocketing to 176 articles in 2022. Notably, in 1995, there were only two articles with the highest CPP_{2022} of 124 citations. This exceptional CPP_{2022} value can be attributed to the influential article titled "Immersive training systems: Virtual reality and education and training" [21] with a TC_{2022} of 198 citations.

The number of articles published each year is clearly on the rise, as seen in Fig. 2, which peaks in 2022 at 176 articles. This indicates a growing interest in VR as a teaching and learning tool and emphasizes how revolutionary this technology can be [45, 46].

Between 1995 and 2018, the average number of citations per publication increased as well; the greatest average number of citations per publication was 124 citations in 1996 [47]. However, the average number of citations per publication decreased between 2018 and 2022, with an average of 3.6 citations per publication in 2022. This implies that while research on VR in education is becoming more popular, the academic community may not give it the same amount of attention as it did in the past.

The rise in publications and citations can be attributed to the increasing awareness of VR technology's potential educational benefits, along with its growing availability and affordability. An immersive and captivating learning environment is offered by VR, which can boost student motivation and make it easier for them to pick up difficult skills and information [48]. However, there are still significant considerations and challenges unique to VR technology, such as the need for effective instructional design and the potential impact of VR on cognitive load [47].

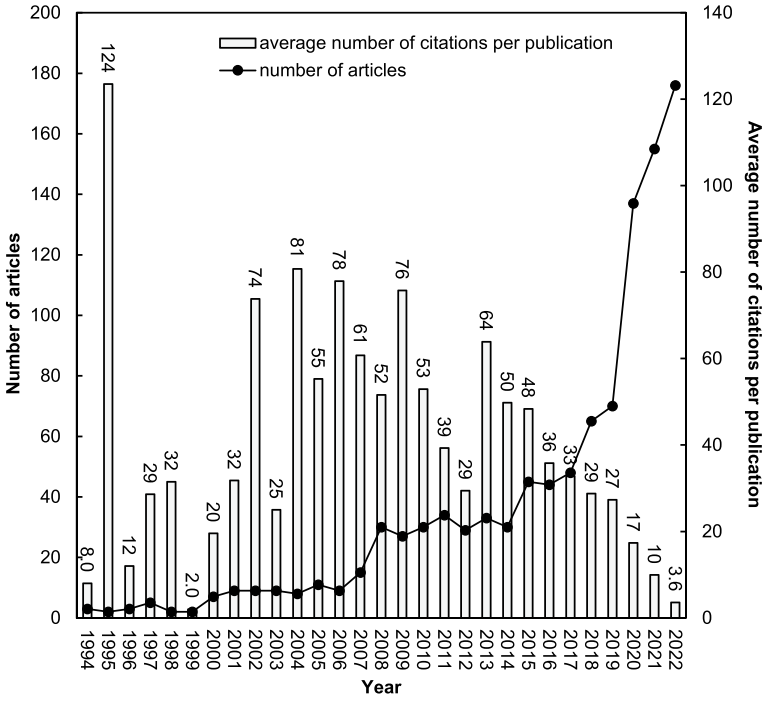

Fig. 2 Number of VR articles in education field and average number of citations per publication by year

In general, the increasing use of VR in the classroom has the potential to have a significant impact on education in the future. To discover the best practices for creating and utilizing VR programs and instructional materials that enhance student learning objectives, more research is necessary. In addition, more study is required to determine how VR affects learning, motivation, and student involvement in addition to identifying any possible risks and difficulties related to this technology. We can make sure that VR is utilized in education efficiently and responsibly by tackling these problems. and that it achieves its greatest potential [45, 46].

3.1.3 Web of science category and journal

Among the journals listed in the SSCI, the education and educational research category stands out with the largest proportion of articles related to VR, accounting for 61% of the total of 1,047 articles. Closely followed by the SCI-EXPANDED category "Education in scientific disciplines" with 39% of articles distributed across 44 journals. The special education category in the SSCI encompasses 4.8% of the articles across 44 journals, while the field of educational psychology features 2.8% of the articles distributed across 61 journals also in the SSCI. Nine of the top ten cited articles were published in the education and educational research category, while one was published in each of the scientific discipline categories. It is worth noting that some journals were classified in two or more categories in the Web of Science Core Collection, as an example, BMC Medical Education was classified under both education and educational research and scientific disciplines education

categories. Therefore, the total percentage of journals in these categories was greater than 100%. This was noted in the study by Ho [49].

The top 10 most productive journals in publishing VR-related articles in the education field were identified, and their impact factors (IF_{2021}), average number of citations per publication CPP_{2022}, and average number of authors per article *APP* were presented in Table 2 Ho [50]. The journal *Computers & Education* ranked first, publishing the most articles (152), which represented 15% of the total articles. When compared to the other top 10 productive journals, articles published in *Computers & Education* had the highest CPP_{2022} of 74 citations, while the *Computer Applications in Engineering Education* had a lower CPP_{2022} of only 9.5 citations. The *APP* varied from 6.5 authors in *BMC Medical Education* to 3.0 authors in *Educational Technology & Society*. Additionally, the journal *Computers & Education* has the highest IF_{2021} of 11.182 and was ranked second in the category of education and educational research.

Next in the list of journals that published VR-related articles in the education field was *Educational Research Review* ($IF_{2021}=10.207$), ranked third in the category of education and educational research, with two articles, The *Internet and Higher Education* ($IF_{2021}=8.591$), ranked fourth in the category of education and educational research, published one article. The *Educational Psychology Review* ($IF_{2021}=93.333$), ranked first in the category of educational psychology, had two articles. In addition, the journal *Academic Medicine* ($IF_{2021}=7.840$), ranked first in the category of scientific disciplines education, published 10 articles related to the topic. However, the *Exceptional Children* ($IF_{2021}=4.091$), ranked first in the category of scientific disciplines education and the *Review of Educational Research* ($IF_{2021}=13.551$), ranked first in the category of education and educational research, did not publish articles related to VR.

3.1.4 Publication performance of countries and institutions

Among the total of 1,047 articles analyzed, a small subset of four articles lacked any affiliations in both the SSCI and SCI-EXPANDED databases. However, the remaining 1,043 articles were authored by researchers hailing from a diverse range of 68 countries. Notably, a

Table 2 The top 10 most productive journals

Journal	*TP* (%)	IF_{2021}	*APP*	CPP_{2022}
Computers & Education	152 (15)	11.182	3.4	74
Journal of Surgical Education	76 (7.3)	3.524	6.3	20
Computer Applications in Engineering Education	56 (5.3)	2.109	3.2	9.5
Interactive Learning Environments	40 (3.8)	4.965	3.6	35
Journal of Computer Assisted Learning	34 (3.2)	3.761	3.6	19
BMC Medical Education	33 (3.2)	3.263	6.5	12
British Journal of Educational Technology	31 (3.0)	5.268	3.2	24
Educational Technology & Society	31 (3.0)	2.633	3.0	27
Education and Information Technologies	28 (2.7)	3.666	3.4	11
Nurse Education Today	27 (2.6)	3.906	4.7	10

TP: total number of publications; %: percentage of articles; IF_{2021}: journal's impact factor (in 2021); *APP*: average number of authors per publication; CPP_{2022}: average number of citations per publication (TC_{2022}/TP)

substantial 83% of these articles were single-country articles, originating from 52 different countries. On the other hand, 17% of the articles emerged from international collaborations, involving authors from 58 countries. Impressively, the internationally collaborative articles exhibited a higher CPP_{2022} value of 34 citations, surpassing the CPP_{2022} of 28 citations associated with single-country articles. This finding suggests that collaborative efforts have a positive impact on the citation count within VR research focused on education.

The study compared the top 15 productive countries (Table 3) using six publication indicators and six related citation indicators. The USA dominated in all six publication indicators with a *TP* of 319 articles, IP_C of 244 articles, CP_C of 75 articles and *FP* of 267 articles, *RP* of 266 articles, and *SP* of 38 articles. Italy had the greatest $TP\text{-}CPP_{2022}$ of 44 citations and $SP\text{-}CPP_{2022}$ of 35 citations, Canada had the greatest $IP_C\text{-}CPP_{2022}$ of 36 citations, Israel had the greatest $CP_C\text{-}CPP_{2022}$ of 106 citations, and Denmark had the greatest $FP\text{-}CPP_{2022}$ of 41 citations and $RP\text{-}CPP_{2022}$ of 42 citations. Overall, six of the top 15 productive countries were in Europe, five in Asia, three in America, and one in Oceania. Only seven countries in Africa published VR-related articles in the education field.

Figure 3 presents the development trends of the four most productive countries in publishing VR-related articles in the education field. The United States was the top country in terms of publication for most of the years. China published its first articles in 2008 and has shown a sharply increasing trend in recent years, reaching the top three in 2022. Therefore, the study indicates that the USA has dominated the publications, but China has shown a significant increase in publishing articles related to VR in the education field.

In terms of institutions, the study found that 46% of the 1,042 VR-related articles in the education field originated from single institutions, with a CPP_{2022} of 28 citations per paper. The remaining 54% were inter-institutional collaborations, with a CPP_{2022} of 28 citations per paper. Of these collaborations, 68% were national collaborations, with a CPP_{2022} of 25 citations per paper, and 32% were international collaborations, with a CPP_{2022} of 34 citations per paper. The study found that international collaborations had higher citation rates than national collaborations. The top 12 productive institutions with ten or more articles and their characteristics are presented in Table 4. Five of these institutions were in the USA, three in Taiwan, and one in Canada, China, Denmark, and Israel respectively. The National Taiwan Normal University ranked first with a *TP* of 31 articles (3.0% of 1,043 articles), followed by the University of Copenhagen, which had a *FP* of 20 articles (1.9% of 1,043 articles) as the first author institution. The Bar-Ilan University had an IP_I of 11 articles (2.3% of 478 single-institution articles) as the institution with the highest number of articles published by a single institution.

The study also found that the Bar-Ilan University ranked first with an *SP* of five articles (4.7% of 107 single-author articles) as the institution with the highest number of articles published by a single author. When compared to the top productive institutions in Table 4, the University of California, Santa Barbara in the USA had the greatest $TP\text{-}CPP_{2022}$ of 99 citations, $IP_I\text{-}CPP_{2022}$ of 106 citations, $FP\text{-}CPP_{2022}$ of 83 citations, and $RP\text{-}CPP_{2022}$ of 83 citations, with 14 articles as *TP*, three as IP_I, four as *FP*, and four as *RP*. The National Taiwan University of Science and Technology in Taiwan with CP_I of 12 articles had the greatest $CP_I\text{-}CPP_{2022}$ of 113 citations. These findings further highlight the various productivity indicators of the top institutions in publishing VR-related articles in the education field.

3.1.5 The citation histories of the top ten most frequently cited articles

In this study, the researchers analyzed the citation histories of the top ten most frequently cited articles. To minimize bias, the researchers considered the total number of

Table 3 Top 12 productive countries

Country	*TP*	*TP*		IP_I		CP_I		*FP*		*RP*		*SP*	
		R (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}
USA	319	1 (31)	34	1 (28)	33	1 (41)	36	1 (26)	33	1 (26)	34	1 (36)	31
Taiwan	130	2 (12)	33	2 (11)	32	3 (17)	35	2 (11)	34	2 (12)	33	2 (14)	10
UK	99	3 (9.5)	33	4 (7.1)	28	2 (21)	41	4 (7.4)	30	4 (7.7)	30	3 (8.4)	34
China	96	4 (9.2)	20	3 (7.7)	16	4 (16)	28	3 (8.2)	19	3 (8.1)	18	6 (3.7)	15
Australia	65	5 (6.2)	34	5 (5.0)	29	6 (12)	45	5 (5.0)	32	5 (5.0)	32	4 (6.5)	20
Spain	49	6 (4.7)	29	6 (4.1)	28	8 (7.7)	33	6 (4.2)	25	6 (4.1)	25	8 (1.9)	4.0
Canada	46	7 (4.4)	33	12 (2.1)	36	5 (15)	31	9 (2.9)	31	9 (2.9)	31	7 (2.8)	10
Netherlands	35	8 (3.4)	16	8 (2.7)	15	9 (6.6)	16	11 (2.4)	15	11 (2.4)	15	N/A	N/A
Germany	35	8 (3.4)	23	8 (2.7)	13	9 (6.6)	42	10 (2.7)	12	10 (2.6)	12	15 (0.93)	26
Turkey	34	10 (3.3)	26	7 (3.5)	28	22 (2.2)	13	7 (3.1)	27	8 (3.1)	27	8 (1.9)	6.5
Denmark	34	10 (3.3)	40	11 (2.2)	31	7 (8.2)	51	8 (3.0)	42	7 (3.2)	41	N/A	N/A
South Korea	26	12 (2.5)	32	13 (2.0)	21	12 (4.9)	52	13 (1.9)	35	13 (2.1)	32	8 (1.9)	18
Israel	24	13 (2.3)	34	10 (2.4)	24	27 (1.6)	106	12 (2.3)	34	12 (2.3)	34	5 (5.6)	10
Brazil	18	14 (1.7)	12	14 (1.5)	7.1	20 (2.7)	23	14 (1.4)	10	14 (1.4)	10	N/A	N/A
Italy	18	14 (1.7)	44	15 (1.4)	36	19 (3.3)	59	15 (1.2)	36	15 (1.2)	36	15 (0.93)	35

TP: total number of publications; *TP R* (%): the percentage of total articles published by each country; IP_C *R* (%): the Rank and percentage of single-country articles in all single-country articles; CP_C *R* (%): the rank and percentage of internationally collaborative articles in all internationally collaborative articles; *FP R* (%): the rank and percentage of first-author articles in all first-authors articles; *RP R* (%): the rank and percentage of corresponding-author articles in all corresponding-author articles; *SP R* (%): the rank and percentage of single-author articles in all single-author articles; CPP_{2022}: average number of citations per publication (TC_{2022}/*TP*); N/A: data is not available

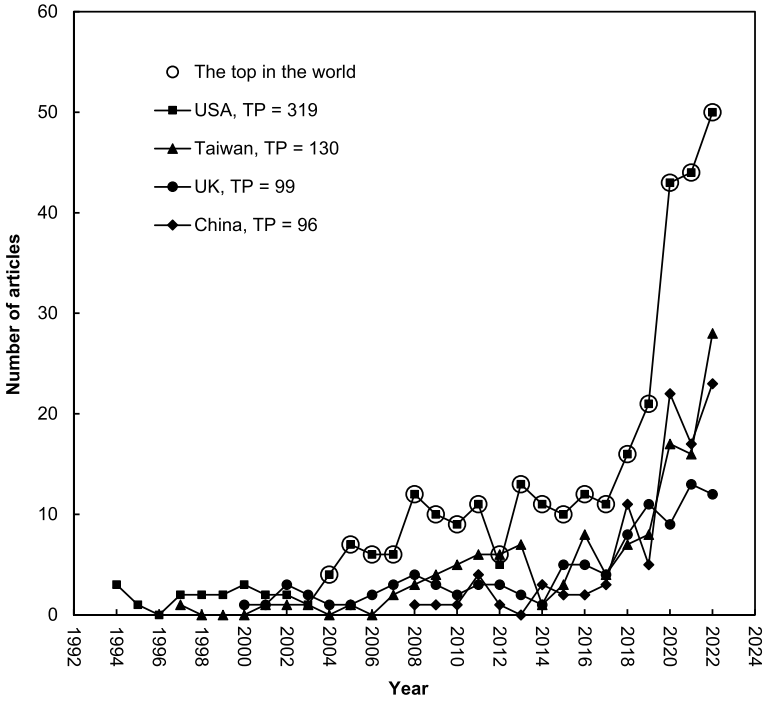

Fig. 3 Development trends of the top five productive countries

citations from the Web of Science Core Collection from the year of publication until the end of 2022 (TC_{2022}) [34]. The analysis revealed that 49% of the 1,047 articles, 77% of the 1,036 articles with abstracts, and 78% of the 929 articles with author keywords had search keywords in present in their titles, abstracts, and author keywords, respectively. Among the top ten most frequently cited articles, four of them had search keywords. Based on these findings, the authors recommended giving more attention to search keywords in the article title or author keywords in bibliometric studies [37]

Table 5 presents the top ten most frequently cited articles, with seven of them published in the *Computers & Education* journal, and one each in *Anatomical Sciences Education, Learning and Instruction, and Interactive Learning Environments*. Furthermore, seven of these articles were also among the top ten most impactful articles in 2022 according to C_{2022} rankings. The researchers emphasized that the citation count of a highly cited article may not always remain high [51], and suggested understanding the citation history of highly cited articles. Figure 4 illustrates the citation histories of the top ten articles. For instance, the article by L. A. 52, 53) ranked fourth with TC_{2022} of 399 citations, but its citation count decreased to 18, placing it 80th in 2022.

Figure 4 and Table 5 provide an overview of the most cited publications related to VR in education. The top-ranked publication, "Current Status, Opportunities and Challenges of Augmented Reality in Education" by Wu et al. [54], has the highest citation count as of 2022, indicating its continued influence in the field. This publication offers valuable insights into the current state of research and development of VR technologies in education. The second-ranked publication, "Assessing the Effects of Gamification in

Table 4 Top 12 productive institutions with 10 articles or more

Institution	*TP*	*TP*		IP_1		CP_1		*FP*		*RP*	
		R (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}
Natl Taiwan Normal Univ, Taiwan	31	1 (3.0)	51	2 (2.1)	15	1 (3.7)	68	2 (1.8)	63	1 (2.7)	51
Univ Copenhagen, Denmark	25	2 (2.4)	48	3 (1.9)	37	2 (2.8)	54	1 (1.9)	55	2 (1.9)	55
Natl Taiwan Univ Sci & Technol, Taiwan	15	3 (1.4)	91	13 (0.63)	2.7	3 (2.1)	113	6 (0.86)	35	4 (1.1)	32
Univ Calif Santa Barbara, USA	14	4 (1.3)	99	13 (0.63)	106	4 (1.9)	98	23 (0.38)	83	27 (0.38)	83
Bar Ilan Univ, Israel	13	5 (1.2)	16	1 (2.3)	16	115 (0.35)	16	3 (1.2)	15	3 (1.2)	15
Florida State Univ, USA	13	5 (1.2)	19	5 (1.5)	25	17 (1.1)	11	4 (1.1)	19	4 (1.1)	19
Stanford Univ, USA	12	7 (1.2)	32	7 (1.0)	68	11 (1.2)	6.4	6 (0.86)	39	6 (0.86)	39
Natl Cent Univ, Taiwan	12	7 (1.2)	30	4 (1.7)	34	35 (0.71)	22	5 (1.0)	34	6 (0.86)	37
North Carolina State Univ, USA	11	9 (1.1)	12	7 (1.0)	16	17 (1.1)	8.2	15 (0.48)	16	15 (0.48)	16
McGill Univ, Canada	11	9 (1.1)	48	N/A	N/A	4 (1.9)	48	23 (0.38)	29	12 (0.58)	32
Chinese Univ Hong Kong, China	11	9 (1.1)	39	13 (0.63)	12	9 (1.4)	49	23 (0.38)	17	27 (0.38)	17
Univ Florida, USA	10	12 (1.0)	32	73 (0.21)	88	6 (1.6)	25	39 (0.29)	38	27 (0.38)	30

TP: total number of publications; *TP R* (%): The percentage of total articles published by each country; IP_1 *R* (%): the rank and percentage of single-institute publications in all single-institute articles; CP_1 *R* (%): the rank and percentage of inter-institutionally-collaborative articles in all inter-institutionally collaborative articles; *FP R* (%): the rank and percentage of first-author articles in all first-authors articles; *RP R* (%): the rank and percentage of corresponding-author articles in all corresponding-author articles; CPP_{2022}: average number of citations per publication (TC_{2022}/TP); N/A: data is not available

Table 5 Top 10 most frequently cited articles

Rank (TC_{2022})	Rank (C_{2022})	Title	Country	Reference
1 (886)	1 (120)	Current status, opportunities and challenges of augmented reality in education	Taiwan	Wu et al. [54]
2 (716)	3 (103)	Assessing the effects of gamification in the classroom: A longitudinal study on intrinsic motivation, social comparison, satisfaction, effort, and academic performance	USA	Hanus and Fox [55]
3 (623)	4 (98)	Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis	USA	Merchant et al. [56]
4 (339)	80 (17)	Investigating the impact of video games on high school students' engagement and learning about genetics	USA	52, 53)
5 (333)	10 (57)	Virtual laboratories for education in science, technology, and engineering: A review	Serbia, the UK, Finland, Austria, Australia	Potkonjak et al. [57]
6 (331)	2 (112)	Adding immersive virtual reality to a science lab simulation causes more presence but less learning	Denmark, USA	Makransky et al. [6]
7 (325)	9 (58)	Investigating learners' attitudes toward virtual reality learning environments: Based on a constructivist approach	Taiwan, USA	Huang et al. (2010)
8 (296)	6 (86)	The effectiveness of virtual and augmented reality in health sciences and medical anatomy	Australia	Moro et al. [78]
9 (295)	12 (54)	Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks	Israel, Spain, Germany, Italy	Gavish et al. (2015)
10 (287)	58 (20)	The effects of computer games on primary school students' achievement and motivation in geography learning	Turkey	Tüzün et al. (2009)

TC_{2022}: the total number of citations an article received from Web of Science Core Collection since the publication year until the end of 2022; C_{2022}: refers to the number of citations an article received only in the year 2022

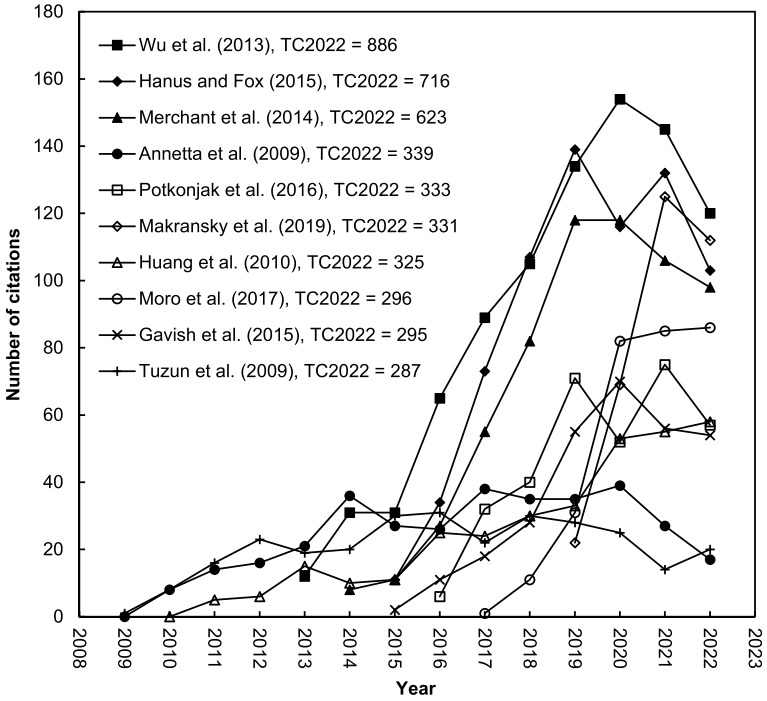

Fig. 4 The citation histories of the top ten most frequently cited articles

the Classroom: A Longitudinal Study of Intrinsic Motivation, Social Comparison, Satisfaction, Effort, and Academic Performance" by Hanus and Fox [55], is also highly cited in 2022. This study highlights the importance of studying specific elements of gamification to understand their effectiveness in promoting intrinsic motivation. According to the study, the authors recommend that to create an ideal gamification system that promotes intrinsic motivation, it is important to isolate specific game mechanics and use theory to evaluate their effectiveness. The study also warns against the use of rewards, badges, and leaderboards, as they are not always effective and can backfire. The authors highlight the need for teachers to carefully evaluate existing empirical evidence before adopting gamification approaches in the classroom.

Other highly cited publications in Table 5, such as "Effectiveness of Virtual Reality-Based Instruction on Student Learning Outcomes in K-12 and Higher Education: A Meta-Analysis" by Merchant et al. [56], "Virtual Laboratories for Education in Science, Technology and Engineering: A Review" by Potkonjak et al. [57], and "Adding Immersive Virtual Reality to A Science Lab Simulation Causes More Presence but Less Learning" by Makransky et al. [6], also offer valuable insights into the potential benefits and challenges of using VR technologies in education. These studies highlight the importance of designing and implementing effective VR-based instructional strategies that promote positive learning outcomes for students.

It is important to note that the publications included in Table 5 come from various countries, indicating that VR in education is a global research topic with the contribution of research conducted in various cultural and linguistic contexts. This underscores

the importance of understanding how VR technologies can be effectively used in various educational settings and contexts.

In summary, the information presented in Table 5 and Fig. 4 suggests that VR in education is a topic of ongoing interest and research. By investigating specific elements of gamification and understanding the potential benefits and challenges of using VR technologies in education, educators and researchers can continue to develop effective instructional strategies that promote positive learning outcomes for students.

3.2 RQ2: Predominant research themes and areas of focus

In recent years, researchers have proposed using the distribution of words in article titles [58] and abstracts [59], author keywords [60], and *Keywords Plus* [60] to identify the main research focuses and their trends in the field of VR in education. The study analyzed article titles, abstracts, author keywords, and *Keywords Plus* during the research period to identify rough trends. The study listed the most frequently used author keywords in VR research in education fields and their distribution in three sub-periods (1993–2002, 2003–2012, and 2013–2022) in Table 6. The most commonly used author keywords included "interactive learning environments", "simulation", "augmented reality", "education", and "simulations" which were used in 85, 61, 50, 40, and 36 articles, respectively. The study found that "simulation", "augmented reality", "interactive learning environments", "education", and "medical education" were becoming more popular in the last study period.

Ho's research group proposed using word distribution in article titles and abstracts, author keywords, and *Keywords Plus* to identify research directions and trends [59, 61]. To find the most often used author keywords and how they changed over time, bibliometric analysis was used for VR research in the education domain. The most significant research questions and the future course of the field's investigation can both be learned a great deal from this analysis.

Table 6 lists the 20 most frequently used author keywords in research on VR in education, as well as their distribution into three sub-periods. The most common keywords used by the authors were "interactive learning environments", "simulation", and "augmented reality". To determine important research avenues, the study used word cluster analysis, utilizing the word analysis results. Figure 5 displays the development trends for seven study fields.

3.2.1 The effectiveness of VR in improving learning outcomes

Integrating VR technology into education can provide students with an immersive and interactive learning experience that improves their training outcomes. As research has shown, VR simulations can offer a personalized, hands-on learning approach that is more effective than traditional classroom methods [62].

Using VR technology, students can participate in simulations that replicate real-world scenarios, allowing them to interact with virtual environments and improve their retention and recall of information. The effectiveness of VR in improving outcomes has been demonstrated by numerous studies, which have identified complementary words such as students (830), training (468), technology (447), practice (362), simulation (194), interactive (85) and personalized (59).

Table 6 The 20 most frequently used author keywords

Author keywords	*TP*	1993–2022 Rank (%)	1993–2002 Rank (%)	2003–2012 Rank (%)	2013–2022 Rank (%)
interactive learning environments	85	1 (9.1)	1 (29)	1 (24)	3 (5.4)
simulation	61	2 (6.6)	N/A	7 (4.9)	1 (7.1)
augmented reality	50	3 (5.4)	N/A	N/A	2 (6.7)
education	40	4 (4.3)	8 (4.8)	13 (3.7)	4 (4.4)
simulations	36	5 (3.9)	8 (4.8)	3 (6.7)	7 (3.2)
training	33	6 (3.6)	N/A	11 (4.3)	6 (3.5)
media in education	31	7 (3.3)	8 (4.8)	7 (4.9)	9 (3.0)
medical education	30	8 (3.2)	N/A	31 (1.2)	5 (3.8)
improving classroom teaching	29	9 (3.1)	N/A	4 (6.1)	11 (2.6)
human–computer interface	28	10 (3.0)	4 (10)	7 (4.9)	15 (2.4)
laparoscopy	26	11 (2.8)	N/A	16 (3.0)	10 (2.8)
teaching/learning strategies	25	12 (2.7)	N/A	4 (6.1)	17 (2)
augmented and virtual reality	23	13 (2.5)	N/A	N/A	8 (3.1)
technology	21	14 (2.3)	N/A	31 (1.2)	11 (2.6)
computer-based learning	20	15 (2.2)	8 (4.8)	N/A	11 (2.6)
pedagogical issues	20	15 (2.2)	N/A	4 (6.1)	28 (1.3)
immersive virtual reality	19	17 (2.0)	N/A	N/A	11 (2.6)
cognitive load	18	18 (1.9)	N/A	N/A	15 (2.4)
multimedia/hypermedia systems	18	18 (1.9)	N/A	2 (7.3)	59 (0.81)
applications in subject areas	17	20 (1.8)	8 (4.8)	7 (4.9)	42 (1.1)

TP: total number of publications; %: percentage of articles; N/A: data is not available

These studies suggest a growing interest in the use of VR for educational purposes and highlight the potential of this technology to improve students' knowledge (362) and skills (226). By providing personalized and interactive learning experiences, VR can help students reach their full potential and gain the skills they need to succeed in their careers [26].

3.2.2 The impact of VR on student motivation and engagement

VR can provide an immersive and engaging learning experience, leading to better retention and recall of information among students [63]. Using supporting words such as environment (409), teaching (344), immersive (104), interactive (85), personalized (59), motivation (49), and engagement (49), studies have demonstrated that VR can increase motivation and engagement.

The interactive nature of VR technology allows students to take an active role in their learning, which can lead to higher levels of engagement and better learning outcomes. By providing students with a sense of presence in the learning environment, VR can create a more immersive and engaging learning experience [64]. The use of VR technology in education has the potential or revolutionize traditional teaching methods by providing students with a personalized and interactive learning environment that improves their motivation and engagement.

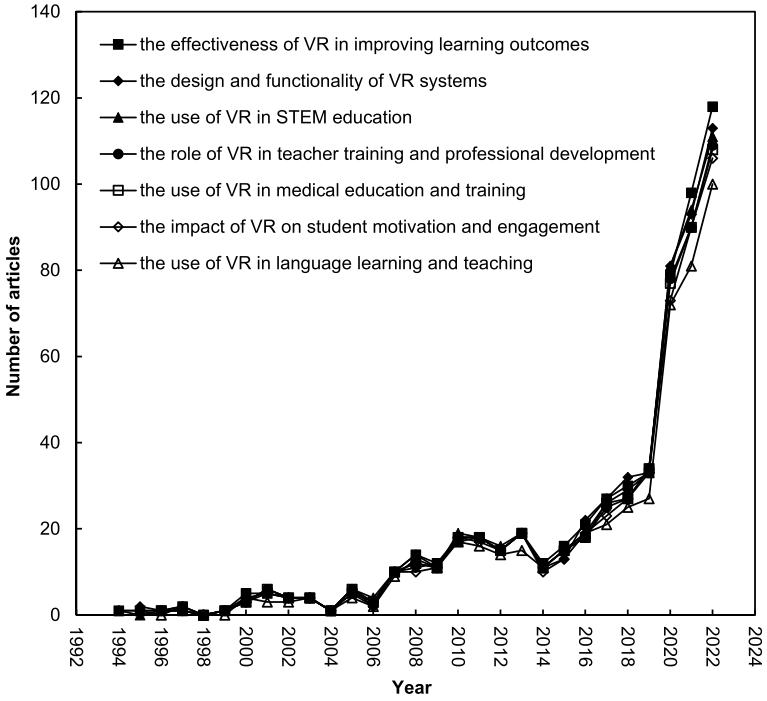

Fig. 5 The development trends of the seven main research focus

3.2.3 The role of VR in teacher training and professional development

VR technology has become a valuable tool for teacher training and professional development, allowing educators to improve their skills in a safe and controlled environment [65]. Using complementary words such as training (468), technology (447), research (293), simulation (194), immersive (104), professional (95), and interactive (85), studies have demonstrated the potential of VR to revolutionize the way teachers are trained and improve the quality of education.

The immersive and interactive nature of VR technology allows teachers to simulate challenging scenarios and experiment with different approaches without risk of harm or negative consequences. This technology can provide teachers with a more personalized and efficient training experience, leading to better classroom experiences for students. The use of VR in training can also improve the professional development of teachers, allowing them to provide higher-quality education to their students. As research has shown, VR has the potential to transform the way teachers are trained and improve the quality of education for students.

3.2.4 The role of VR technology in medical education and training

The use of VR technology in medical education, particularly in areas such as surgery and laparoscopy, is becoming more common [66], using complementary words such as training (468), simulation (194), immersive (104), interactive (85), surgical (40), medical (30) and

laparoscopy (26), studies have demonstrated the potential of VR to revolutionize the way healthcare professionals are trained and to improve the quality of care for patients.

Medical professionals and trainees can hone their surgical abilities and lower their chance of error during actual surgical procedures by practicing in a safe and controlled setting with VR simulators. Compared to conventional training techniques, this technology can offer a more engaging and dynamic training experience. The use of VR in medical education has the potential to improve surgical outcomes because well-trained surgeons are better equipped to perform complex procedures. As studies indicate, VR can revolutionize training methods for healthcare professionals and improve the quality of care provided to patients.

3.2.5 The design and functionality of VR systems

The effectiveness and usability of VR systems in education depend on their design and functionality [67]. Utilizing supporting words such as design (455), augmented reality (104), virtual-reality (64), innovation (29), user interface (28), human–computer interaction (28), and multimedia (18), studies have demonstrated the importance of well-designed VR systems with intuitive use interface that is easy to navigate.

The human–computer interaction in VR systems should be seamless and natural, allowing users to interact with virtual objects and environments in a way that feels intuitive and realistic. Innovations in VR design and functionality can improve the user experience and make VR technology more accessible. The use of VR, augmented reality, and multimedia technologies can also enhance the effectiveness of education and improve learning outcomes. Effective VR systems should be designed to be both immersive and interactive, with features that enhance learners' engagement, motivation, and learning outcomes. As research has shown, the design of VR systems is a crucial factor in the development of effective educational tools.

3.2.6 The use of VR in language learning and teaching

VR technology has the potential to revolutionize language learning and teaching by providing immersive and interactive learning experiences [68]. Utilizing supporting words such as technology (447), teaching (344), simulation (194), interactive (85), immersive (104), personalized (59), and language learning (31), studies have demonstrated the effectiveness of VR in improving learners' motivation and achievement.

By transporting language learners to different virtual environments, VR technology can provide a unique learning experience that enhances learners' engagement and motivation. The personalized nature of VR technology can also provide learners with tailored language learning experiences that meet their specific needs. However, it is important to note that VR technology is still a relatively new tool in language learning and may not be accessible to all learners [69]. Further research is needed to fully understand the effectiveness of VR in language learning and to identify best practices for its use in different contexts and for different types of learners.

3.2.7 The use of VR in STEM education

VR technology has the potential to enhance STEM education by providing immersive and interactive simulations that enable students to explore scientific concepts in a hands-on

way [70]. Utilizing supporting words such as technology (447), hands-on (362), simulation (194), science (112), immersive (104), interactive (85), and STEM education (17), studies have shown that VR can improve student achievement and motivation in STEM subjects such geography [71].

VR simulations can provide students with immersive and interactive learning experiences that improve their understanding and engagement with complex scientific concepts, as well as enhance their critical thinking and problem-solving skills (L. [52, 53, 72, 73]). This makes VR technology a promising tool for transforming STEM education and preparing students for success in STEM fields. Additionally, VR technology can provide students with hands-on learning experiences that deepen their understanding of STEM subjects [74]. As such, understanding the current state of research on VR in education and its potential for enhancing STEM education is crucial for educators and policymakers [73].

The extensive research on VR technology in education has made it challenging to define the scope and keywords for this study. However, our analysis confirms that while different research topics may have unique supporting words, there are some overlapping themes and keywords that can be found across diverse research areas. For instance, simulation-based assessments have been identified as a key area of research in VR technology, as they have been shown to enhance learning outcomes, student motivation and engagement, and teacher training and professional development, among other aspects of learning and training.

Additionally, our analysis highlights the multifaceted nature of VR technology, which can be employed in various contexts and for different purposes, such as immersive learning, interactive learning, computer simulation, personalized learning, and education technology. Therefore, a careful selection of keywords and a systematic approach to the literature review were essential to ensure a comprehensive analysis of the current state of research in VR in education, as different research topics may have unique aspects and specialized vocabulary [27].

Jingili et al. [75] conducted a bibliometric analysis of the use of VR in addressing depression and anxiety from 1995 to 2022, which is in line with the larger research topics identified in the field of education and technology. This finding is consistent with the results of our bibliometric analysis. This alignment reinforces the importance of focusing on these topics, as researchers can contribute to the development of innovative technologies and approaches that have the potential to improve learning outcomes, enhance training, and transform education and healthcare. The insights gained from bibliometric analysis can help inform research priorities and identify potential collaborators and research directions in the field, as demonstrated by the VR use in addressing depression and anxiety. The findings of Jingili et al. [75] suggest that VR technology has the potential to be an effective tool for addressing mental health challenges, which is also consistent with our findings. Therefore, conducting bibliometric analyses in various fields, including VR technology, can provide valuable information and guidance for researchers, policymakers, and stakeholders in addressing complex societal challenges.

3.3 RQ3: Challenges and solutions

VR technology has shown great promise in enhancing education. However, its implementation also presents several challenges that need to be addressed. This bibliometric study covers a period from 1993 to 2022 and includes an analysis of the most cited papers published

between 2014 and 2022. It focused specifically on the challenges associated with the use of VR in education, by identifying the key challenges that have emerged in the past decade.

Insufficient Research Evidence and Conversion Challenges: one of the primary challenges in implementing VR in education is the lack of sufficient research evidence supporting the conversion of conventional instruction or desktop VR simulations into immersive VR experiences [76]. The limited evidence calls for cautious investment in VR implementation, and wholesale replacement of conventional media with immersive VR for teaching basic scientific knowledge is not recommended. Instead, combining VR with generative learning strategies, such as summarization, can enhance its effectiveness.

Maintaining Learner Motivation and Engagement: another significant challenge is maintaining learner motivation, interest, and engagement when using VR [76]. Efforts must be made to ensure that VR should not diminish these factors. Combining VR with conventional media and generative learning strategies can help spark interest while maintaining comparable learning outcomes.

Addressing Individual Differences and Ensuring Rigorous Evaluations: in conducting research on VR in education, there are threats due to differences in instructional medium, method, and content, which can impact the validity of the results [76]. To address this, research strives for experimental control and mitigation by using consistent words and graphics in lessons. Additionally, the findings related to VR's effectiveness are context-dependent, and it is recommended to replicate studies in different learning contexts to determine generalizability [77]. Moreover, the introduction of VR creates novelty, excitement, and motivation, which can influence students' performance and pose challenges in assessing the impact of VR. To mitigate the novelty effect, studying students using desktop VR over multiple terms is recommended.

Integrating Dynamic Elements and Designing Effective Pedagogical Environments: Integrating dynamic elements into virtual laboratories and educational environments is a challenge that needs attention [57]. The state-of-the-art in virtual worlds requires restricting to introduction of system dynamics, which poses challenges in designing effective virtual laboratories. Furthermore, the implementation of immersive education, distance learning, and virtual worlds raises pedagogical questions that require further exploration [57].

Managing Potential Negative Side Effects: The use of VR in education can lead to potential negative side effects such as cyber sickness, particularly in the context of learning anatomy [78]. Addressing cyber sickness and its adverse effects on learning experiences should be a priority in virtual and augmented anatomical education.

Gamified Courses and Individual Differences: In the context of gamified courses, challenges arise regarding motivation, satisfaction, and empowerment. Gamified courses can lead to a decrease in students' motivation, satisfaction, and empowerment over time compared to non-gamified courses [55]. It is important to consider the potential harm to intrinsic motivation caused by rewards and competition in gamified courses. Individual differences and contextual factors, such as performance anxiety and confidence, need to be taken into account when implementing gamification [55]. When integrating gamification in the context of VR, it is crucial to address the potential benefits and challenges, ensuring a balance between engagement and individual needs.

Technology-Centered Approach and Overstimulation: Adapting learning material to immersive VR alone does not ensure better learning outcomes. Principles of instructional design and immersive VR should be considered in parallel [6]. VR functionalities that are very stimulating have the potential to cause cognitive overload and hinder learning. In fact, to avoid learning overload, cognitive processing and sensory input must be balanced. Cognitive Load and Control Mechanisms: Lab simulations,

including immersive VR, are challenging for students. Managing cognitive load in immersive VR experiences is important to ensure appropriate challenge levels and prevent overwhelming learning [6]. Additionally, the control mechanisms used in immersive VR simulations were not intuitive for participants. User-friendly and intuitive control systems are essential for enhancing the learning experience.

4 Discussions

This study conducted a bibliographic analysis of 1,157 relevant articles on VR in education to understand the pedagogical effectiveness of such innovation and address associated considerations and challenges in education settings. Similar to the previous studies by [24, 26], Yu [79], Rojas-Sánchez et al. [25], Tiwari et al. [80], and Parmaxi [81], this study's findings highlighted key benefits and considerations of using virtual reality (VR) in education. According to the findings, VR can provide an immersive and interactive learning experience for students which is also supported by Marougkas et al. [26]. This capability of VR can significantly enhance understanding of complex concepts and promote engagement among learners in educational settings. Findings were also aligned with Yu [79], who reported positive impacts of VR on educational outcomes, including increased motivation and satisfaction. Similar to Rojas-Sánchez et al. [25] and Tiwari et al. [80], this study's findings emphasized the growing acceptance and integration of VR in education. This accelerated exploration of VR has led to greater recognition of its benefits and wider adoption in traditional and online education. Tiwari et al. [80] specifically highlight VR's significant contribution to teaching across various disciplines in online education. This study found that VR can significantly enhance language teaching and learning. This finding is also supported by Parmaxi [81], who indicated that VR has the potential to improve language skills, teamwork, autonomy, and cultural awareness.

Moreover, the findings align with previous studies supporting the positive impact of VR on educational outcomes, such as motivation and satisfaction. However, this research delves deeper into specific factors contributing to these outcomes, identifying design elements or instructional strategies that optimize VR's benefits. These actionable insights benefit educators and instructional designers. Further, this research addresses challenges associated with VR implementation in education, shedding light on potential solutions. This study identifies effective approaches for reducing cognitive load, addressing accessibility, and ensuring equal opportunities in VR-based educational experiences. These insights optimize VR integration in education. In general, findings contribute additional evidence, insights, and practical implications for the use of VR in education. By expanding current knowledge, this study enhances understanding of VR's benefits, challenges, and strategies, supporting its effective utilization in educational settings.

By analyzing a substantial number of articles, this study provides in-depth insights into research output, adoption rates, and trends across countries and institutions. It also addresses the challenges associated with VR integration in education and proposes solutions to overcome them. This study complements existing research by offering a broader overview of the current state of VR integration and its implications for educational practices. Furthermore, it serves as a practical roadmap for implementing and improving VR

technology in education, emphasizing the need for further research on the pedagogical aspects of VR and advocating for collaboration and knowledge-sharing in the field.

5 Conclusion and implications

This bibliometric study provides valuable insights into the current state of research on the use of VR in education. The analysis reveals a growing interest in the application of VR technology for educational purposes, particularly in skill development and training, and highlights the need for future research on the pedagogical effectiveness of this technology. The study's findings can be used by VR service providers and educational institutions to pre-plan for strategic investments in VR technologies. Considering the increasing attention to VR for educational purposes, allocating resources to the adoption of VR technologies and content into educational platforms can give an advantage over competitors. Education program directors can work with VR developers to create dynamic and engaging learning environments that support different students' needs and learning goals. Meanwhile, to accelerate the process of VR adoption, educational institutions can offer related training courses and workshops to improve the skill development of their academic staff.

The study identifies several challenges that need to be addressed to ensure the successful integration of VR in education settings. One of the key challenges is the potential compromise of learning outcomes due to the novelty and excitement surrounding VR technology. Educators need to carefully design VR experiences that align with specific learning goals and strike a balance between immersion and educational objectives. By addressing these challenges, educational institutions can maximize the potential benefits of VR technology in education.

Furthermore, the study provides information on the publication performance of various countries and institutions, which can guide future collaborations and partnerships in the field of VR in education. Considering the dominance of single-country articles, collaboration among educators, researchers, and policymakers from diverse countries is recommended to promote knowledge exchange in the field of VR in education. Meanwhile, the citation histories of the most frequently cited articles demonstrate the impact of seminal works in this field and highlight the need for interdisciplinary collaborations between computer science and education research to advance the field.

Overall, this bibliometric study presents a comprehensive overview of the current state of research on VR in education, including key research areas and trends, and the publication performance of countries and institutions. The insights gained from this analysis can inform future research directions and policy decisions related to the use of VR technology in education. As VR technology continues to improve and become more accessible, it has the potential to revolutionize the way we learn and teach, and this study provides a foundation for future research in this exciting and rapidly evolving field.

Considering the increasing demand for VR, service suppliers are recommended to provide sufficient training and skill development to showcase the technology's potential to improve educational opportunities. Meanwhile, educational managers can work on training academic staff on how to use VR tools in teaching and learning situations more effectively. In light of the ongoing research required to explore the pedagogical effectiveness of VR technology, managers should allocate specific resources and funds to identify the best approaches to incorporate VR into educational curricula to elevate

learning outcomes. Managers are advised to establish and incorporate long-term strategic planning for the adoption and usage of VR into educational practices. This can involve continually assessing the most recent scientific findings and consulting with education experts, and then revising plans of action appropriately.

It is important to acknowledge that bibliometric analysis has its limitations, such as potential biases in article selection and the use of certain keywords. Future studies could benefit from a more detailed discussion of these limitations. Additionally, a more detailed analysis of the theoretical frameworks and educational models that underpin the use of VR technology in education could provide further insights into the pedagogical effectiveness of this technology. These considerations could inform future research directions and collaborations in the field of VR in education.

Future research directions in the field of VR in education may include investigating augmented reality, augmented and virtual reality, immersive virtual reality, and cognitive load. Furthermore, exploring the theoretical frameworks and educational models underlying VR technology can enhance our understanding of its pedagogical effectiveness, contributing to advancements in this field.

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Declarations

Conflict of interest The authors declared that they have no conflicts of interest in this work.

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