



Immersive frontiers: A two-decade bibliometric analysis of virtual and augmented reality research in science education (2006-2026)

Natalia A. Orekhovskaya ^{1*}

 0000-0001-8390-5275

Marina N. Svintsova ¹

 0000-0002-9402-0816

Olga V. Shevchenko ¹

 0000-0002-4883-603X

Evgeniya S. Buzhor ¹

 0000-0002-2724-9565

Nina O. Voskresenskaya ¹

 0000-0002-2014-6790

Mikhail S. Miroshkin ¹

 0000-0002-7964-935X

¹ Financial University under the Government of the Russian Federation, Moscow, RUSSIA

* Corresponding author: naorehovskaya@fa.ru

Citation: Orekhovskaya, N. A., Svintsova, M. N., Shevchenko, O. V., Buzhor, E. S., Voskresenskaya, N. O., & Miroshkin, M. S. (2026). Immersive frontiers: A two-decade bibliometric analysis of virtual and augmented reality research in science education (2006-2026). *Contemporary Educational Technology*, 18(4), Article ep697. <https://doi.org/10.30935/cedtech/19596>

ARTICLE INFO

Received: 11 Aug 2026

Accepted: 1 Oct 2026

ABSTRACT

During the last twenty years, virtual and augmented reality applications have become a key component of science education. However, there is no systematic analysis of the intellectual basis of scientific research in this area. A bibliometric study of 116 articles published in peer-reviewed journals listed in Scopus in 2006-2026 was carried out, during which the performance of the authors was analyzed using the *bibliometrix* R software and co-authorship, co-citation, and keyword co-occurrence networks were created using the VOSviewer software. All articles had 4,742 citations with an average of 40.88 and an h-index of 33; the authors of the articles came from 42 countries; the most productive ones are the United States, Australia, China, and Greece. Five articles have received 44% of all citations and represent the major theoretical contributions, including the importance of embodied VR-based learning and the role of such learning environments in fostering students' understanding of physics and biology concepts. Based on the keyword co-occurrence analysis, the articles can be grouped into four clusters, characterized by the common themes of immersive and embodied learning, disciplinary learning, the use of augmented and mixed reality, and computer science education. The paper contributes to the understanding of the scientific basis of VR and AR applications for science education: it was found that the area is based on the concepts of embodiment, presence, and situated meaning, which integrate into the common framework.

Keywords: virtual reality, augmented reality, science education, bibliometric analysis, immersive learning

INTRODUCTION

The ability to visualize and manipulate phenomena that are typically invisible, unsafe, abstract or remote has been an integral part of science education. Atoms are invisible, the orbits of planets can't be touched and some chemical reactions are too risky to conduct safely in your regular classroom. Diagrams and physical models, along with lab demonstrations have been used by science teachers, for decades, to convey “real” learning experiences to abstract scientific concepts. Virtual reality (VR) and augmented reality (AR) technologies have taken the toolbox of “pedagogical” a giant leap forward and increased the number of applications available in the classroom—from viewing the inside of a cell to holding a molecule in your hand, standing on the surface of Mars, and more—without even leaving the classroom (Lindgren et al., 2016; Moro et al., 2017).

VR is the computer-generated environment, which surrounds the user while he is in a simulation of a 3D world, usually using a head-mounted display (HMD), and AR is the addition of digital information onto the reality world where the learner can interact simultaneously with reality and virtual elements (Huang et al., 2019). These technologies were originally designed for military applications or entertainment, but in the last 10 years, the great ease with which such technologies can be accessed, improvements in the resolution of displays, and the emerging realization of the pedagogical benefit of embodied and situated learning experiences (Johnson-Glenberg & Megowan-Romanowicz, 2017; Johnson-Glenberg et al., 2014) has led to a significant increase in the extent to which such technologies can be used in science education.

There are several theoretical aspects that have converged in science education, in the context of the virtual and AR. Regarding concepts as abstract knowledge that is “grounded” in body experiences, embodied cognition theory holds physical action and gesture are not only able to be significant aspects of knowledge acquisition but also integral aspects of knowledge (Lindgren et al., 2016). In certain situations, immersive simulations can also model a context that supports the construction of knowledge: where and how the knowledge is going to be used—as the situated learning theory suggests (McElhaney & Linn, 2011). Besides, in virtual environments (VE), researchers have identified a unique perceptual sense of being in a real space within a simulated environment, which appears to enhance emotional involvement, motivation, and learning success (Makransky et al., 2020).

Despite the various scientific theories and empirical studies that support the involvement of VR and AR in science education, the literature is not consolidated yet, and the number of studies conducted were distributed in five subjects: educational psychology, computer sciences, instructional design, science education, and research education. The breadth of studies is in many other ways deep, as it relates to an array of different science domains (e.g., physics or chemistry students), focuses on various groups of students (K-12, teacher preparation, and undergraduate), technological modalities (desktop VE, mobile AR applications, and HMDs), and methods (experimental, quasi-experimental, qualitative, and design-based research). This diversity also makes research, curriculum development, and policy making challenging, as one is hard pressed to spot the general development patterns, influential work, and define a coherent research agenda, since the field remains fragmented across disciplinary “silos.”

Bibliometric analysis is “a systematic, quantitative method that forms descriptions of the intellectual structure of a research field. Bibliometric methods are tools that allow scientists to have a wide overview of the discipline and adopt some features of scientific evolution, productiveness and conceptual structure in the form of publication and citation patterns, co-authorship patterns and even the frequency of words for co-occurrence in a large body of scientific literature (Donthu et al., 2021; Zupic & Čater, 2015). Although VR and AR have been used in a broad variety of subfields in educational technology, a comprehensive bibliometric synthesis study about VR-AR in science education has not been conducted. While some subfields of educational technology like AI in learning (Zawacki-Richter et al., 2019) and mobile learning (Sung et al., 2016) have incorporated these analyses, a comprehensive literature review on the use of VR and AR in science education is missing in the literature.

To fill this void, the present study conducted a bibliometric analysis of journal articles on VR and AR in science and STEM education published between 2006 and 2026 and indexed in Scopus. This two-decade long period shows the whole spectrum of the field's evolution, from the first experimental research conducted

with the simplest (VE built on the desk) to the most recent researches involving consumer grade HMDs, AR application on mobile devices, and the newest explorations of science learning platforms based on the metaverse. The analysis is guided by the four research questions (RQs) outlined in the method section below, addressing the trend of publications, impact of citations, thematic structure and time evolution.

This study has a number of contributions to make. First and foremost, it is the largest compilation of VR and AR studies available anywhere, but with a selective lens marrying science education to VR and AR technology, as opposed to the many studies on science ed tech in the wider literature. Second, it identifies the main publications, authors, and journals that are shaping the field and offers a 'road map' for anyone just embarking on this field of enquiry. Third, it exemplifies a conceptual structure of the field, obtained in the form of a keyword co-occurrence graph that depicts the key thematic clusters of the field and their connections. The fourth part examines the progression of research areas over different years, offering a more detailed look at the evolution of the enduring research themes and the new ones like mixed-reality and handcrafted immersive learning environments assisted by AI (Gonzalez et al., 2017). These all work toward designing the future research, curriculum development and science education policy development for immersive technology in science education.

LITERATURE REVIEW

Theoretical Foundations of Immersive Technology in Science Learning

There are a number of related theoretical streams that have been the foundation for research on VR and AR in science education. Embodied cognition theory claims that the internal cognitive processes are constrained by the body's environment, including both the actual and the imagined; gestures, movements and body orientation are not, therefore, periphery products of cognition but part and parcel of some of the most basic mechanisms of knowledge construction (Johnson-Glenberg et al., 2014; Lindgren et al., 2016). Theoretically, this lens has been expressed in a variety of ways in so-called immersive science learning environments such as motion-capture systems and embodied interaction paradigms, enabling learners to perform scientific phenomena, such as motion of the planets or molecular bonding, rather than just see static depictions of those phenomena (Johnson-Glenberg & Megowan-Romanowicz, 2017).

A second critical theoretical perspective that is specific to immersive media is provided by the theory of presence. Presence is the subjective psychological feeling of being physically situated in a VR when the participant knows that the VE is computer simulations (Makrasky et al., 2020). At higher levels of presence, emotional involvement, debriefing of extraneous mental processes and better learning of scientific material have been found, but the relationship between presence and learning outcomes varies according to such factors as the learner's prior knowledge, simulation fidelity and the design of the instructional scaffolds used in the accompanying debriefing (Makrasky & Petersen, 2021).

Situated learning theory also sets situated learning as a useful key to the pedagogical use of VR/AR as learning products are best acquired when they are intrinsically connected to environments that are realistic and context-rich and that reflect real scientific practice (McElhaney & Linn, 2011). For example, learners can use virtual chemistry laboratories to conduct learning-by-doing, exploratory experiments that they could not practically carry out in a laboratory setting due to the cost, safety or logistic issues (Hu-Au & Okita, 2021; Reeves et al, 2021). Lastly, the theory of cognitive load has been extensively used to analyze the design of simulated environments when the pedagogy is science education because, in poorly designed simulations, cognitive resources for extraneous perceptual detail can compete with that needed for the germane aspects of cognition needed for developing scientific knowledge and understanding (Liu et al., 2022).

VR Applications in Science Education

VR science applications range from low-immersion (desktop) VR simulations to full-immersion (HMD) VR applications. While research in this field has been limited, the use of VE for examining various consequences related to inquiry-based science and pedagogy has been outlined by early work, such as Kennedy-Clark's (2011) research on scenario-based virtual worlds for pre-service science teachers. This notion was further developed in following work in specific science disciplines, particularly chemistry education, where the

development of procedural laboratory skills, conceptual understanding of chemical processes and problem-solving skills was seen to benefit from use of virtual laboratories, while significantly decreasing the level of safety endangering, assessable materials and equipment used for physical/laboratory-based instruction (Reeves et al., 2021; Scherer & Tiemann, 2012).

One prominent area of VR research is the embodied and motion-captured simulations in which students physically negotiate a VE, manipulating physical objects in the VE that represent scientific properties like a planet's movement or the propagation of a wave. In engineering, Johnson-Glenberg et al. (2014) showed this collaborative embodied learning to be highly effective for conceptual content learning, which has been confirmed and built upon in physics education settings (Johnson-Glenberg & Megowan-Romanowicz, 2017). Lindgren et al. (2016) also reported greater learning outcomes and more student engagement in a VR simulation of planetary motion combining embodied interaction with no VR, which provided one of the most frequently cited empirical bases for embodiment-based teaching with VR in science.

In the last 10 years, however, research on immersive VR HMDs has grown significantly thanks to the introduction of the consumer VR glass. There is potential for the affective and motivational power of immersive technology to extend beyond initial content learning to extended learning and career paths, as Makransky et al. (2020) have shown immersive VR simulations may be an effective way to increase secondary school students' interest in and aspirations for science and future careers. Likewise, Liu et al. (2022) noted that academic achievement, motivation, and cognitive load, compared to normal classroom instruction, were higher in immersive VR classrooms, but decreases in cognitive load were less for certain science topics and constituents due to variations in both types of science and with the individual student characteristics investigated.

AR and Mixed Reality in Science Instruction

In the context of immersive science education research, the AR field can lie on a different continuum and can be an enhancement to physical space, in some cases by constructing a dedicated digital space. The combination of these qualities arises a need for the AR to be well suited for use instances on which the combination of physical and virtual data sources provides the learner with supplementary information, such as: Anatomical studies, geological field works, astronomical studies (Arvanitis et al., 2009). The results showed that both modalities could assess learning gain over the traditional level of learning, although such gains cannot be compared across modalities given the various science contents and the specific science tasks' demands on spatial reasoning in the current studies. The results indicated that both modalities measured a gain in knowledge compared to traditional just as much, but the benefits of the type of instruction varied based on type of science content and the requirements of spatial reasoning for the science task.

AR and VR technologies are combined in a more revolutionary way in teaching and learning. Learning in mixed reality (MR) is an approach to learning where the learner can interact with a spatially anchored 3D digital object, usually through very high-tech headsets with the added capability to map the world. Cowling and Birt (2018) presented paramedic science education an approach to the adoption of this MR, as a way to support the rapid technological and pedagogical development process that is iterative.

Some studies have started to focus on AR, VR, and MR technologies, but few comparative research studies have investigated the pedagogical advantages of AR, VR and MR technologies. While the integrative review by Chang et al. (2023) uncovered no approach of digital literacy that applied to all three technologies, they did suggest that technologies should be selected for teaching and learning purposes instead of the novelty of a single technology. It is important to note that developing technology-confident teachers, is not enough for science learning to be successful when teaching with technology and that the effectiveness of science learning using immersive science learning model is highly correlated with the science learning principles used and the affordance of technology used (Mystakidis & Christopoulos, 2022).

Disciplinary Applications Across the Science Curriculum

VR and AR applications have been studied throughout the entire science curricula with some of the areas gaining more academic focus than others. A specific topic where embodied VR research has started is physics education, which has a high demand for spatial or kinematic reasoning that suited very well to the embodied interaction affordances of the immersive technology (Johnson-Glenberg & Megowan-Romanowicz, 2017). To

further investigate such an embodied approach in the teaching and learning of the thermodynamics field, Xing et al. (2023) targeted the teaching and learning of traditionally abstract thermal concepts in the field of thermodynamics with augmented interaction and learning analytics.

A second application area is chemistry education, where virtual laboratories can offer safe, repeatable and cost-effective access to chemical processes and apparatus that might be unsafe or require expensive consumables (Hu-Au & Okita, 2021; Paxinou et al., 2020). Building on this research, Flegr et al. (2023) designed an intervention to directly compare and contrast the effectiveness of employing both virtual and real laboratory environments within the same instructional sequence: the combined VR+RL approach created brand new conceptual increases compared to any of the other options. Petersen et al. (2022) found that pipetting performance in virtual reality could predict real-life pipetting performance, and Yang et al. (2024) showed that an exploration-based spherical video-based VR approach promoted students' chemistry learning effectiveness.

Finally, astronomy and earth science education has also greatly improved, given the intangibility of the astronomical and earth science phenomena that cannot be directly visually observed in its own environment in the classroom. Kersting et al. (2021) investigated the extent of engagement in an astrophysics VR journey carried out at a public science festival, highlighting the potential of the immersive nature of astronomy experiences to create real-world public engagement with complex science beyond the walls of formal classroom education. Kersting et al. (2024) later reflected on design principles for astronomy VR through a dialogue between researchers and practitioners. Another large application area is biology and health sciences education, where one of the most cited contributions to the scientific education literature is the systematic comparison of the effectiveness of VR and AR in anatomical education by Moro et al. (2017), the impact of which is still far-reaching into any number of other applications of VR and AR in health sciences education. Schloss et al. (2021) further extended this anatomical study and their findings to functional neuroanatomy, concluding that the immersive virtual brain environment would also "facilitate spatial learning to support spatial comprehension of neural structures, which are otherwise notoriously hard to communicate with conventional two-dimensional diagrams. The impact of VR on high school students' motivation to study science courses, reported by Garduño et al. (2021), also highlights the affective benefits of immersive technology in secondary education, supporting the work of Makransky et al. (2020) which reported similar findings regarding the high school chemistry experiment.

Teacher Preparation and Professional Development

Many of the scientific literature will be dedicated to the aptitude of science teachers to implement technologically VR/AR. Through a quantitative study, Lamb and Etopio (2020) investigated whether using VR as a tool would help preservice science teachers transfer their theoretical knowledge of pedagogical methods into the classroom and concluded that hands-on experience with VR in teacher preparation programs increased the teacher candidates' confidence in pursuing pedagogical planning. Similarly, Artun et al. (2020) showed that the lab tasks conducted in VR enriched classrooms resulted in positive outcomes for science process skills knowledge among pre-service science teachers, thus proposing that VR has a dual pedagogical role, it not only helps improve science processes skills of end users but also helps model an effective technology-integrated pedagogy to pre-service science teachers.

Recent research has looked at teacher attitudes and behaviors to better understand teacher uptake of immersive technology. Ogegbo et al. (2024) explored the willingness of pre-service science teachers to adopt and implement VR classrooms in science education and found that perceived usefulness, technological self-efficacy, and institutional support were important factors in predicting people's intentions to adopt VR classrooms. Ateş and Kölemen (2025) furthered this line of research on gamified VR adoption from the adoption perspective, by combining multiple theories of technology acceptance into a unified predictive model for science teachers and showed that perceived enjoyment and curricular alignment were significant in predicting VR adoption beyond the more traditional constructs of usefulness and self-efficacy. This research strand aligns with existing frameworks of technology acceptance and further investigates this question in the context of VR and AR in the science classroom, demonstrating that technology use in science classrooms goes beyond simply having the technology, emphasizing the role of teacher beliefs and the preparedness of the school and district to accept and cultivate VR and AR technology.

Effectiveness Evidence and Methodological Considerations

The evidence that has been gathered around VR and AR STEM comes in many different forms and studies are intrinsically complex. However, there are several reports showing positive impacts on conceptual understanding, motivation, and engagement (Lindgren et al., 2016; Liu et al., 2022; Makransky et al., 2020; Xie et al., 2023), on the other hand, there are also a number of reports highlighting the absence of results or mixed results, especially when the immersive technology is mismatched with specific learning aims and learning results may be complicated by extraneous technological novelty effects (Parmar et al., 2023). The systematic literature review performed by Ullah et al. (2022) revealed that learning outcomes of using a serious game in science education are mostly positive, but this may vary in magnitude and persist according to the quality of the instructional design, the number of hours the game was used, and the desired cognitive and affective learning outcomes.

Common methodological flaws found throughout the primary literature involve small sample size, brief intervention length, lack of long-term retention measures, and using subjective measures of engagement and presence instead of objective behavioral and physiological measures (Poonja et al., 2023). A very interesting exception is Hite et al. (2019) who examined how a haptic (tactile) capable VR based science education intervention contrasted in its perception of presence across the different cognitive development stages of adolescents, highlighting age-based development progressive interpretations of presence effects that may not be transferable. Pande et al. (2021) directly addressed the longitudinal evidence gap, conducting a longitudinal study of immersive VR simulations in undergraduate science learning which, for this reason, are scarce with respect to evidence of the durability of learning gains brought about by VR interventions beyond the immediate postintervention period. This is a relatively under-explored approach in the existing literature and is one methodological area that the present bibliometric analyses suggest warrants increased research investment.

METHOD

This study uses a bibliometric research design approach to systematically analyze the scientific literatures produced and published by their peers on the virtual or AR use in science education. Bibliometrics is a quantitative application of publication and citation data which helps to describe the structural and intellectual trait of the research field, repeatable and objective, in a way that represents its nature (Pritchard, 1969; Zupic & Čater, 2015). The methodological approach taken here reflects the two-stage approach recommended by Donthu et al. (2021): Performance analysis and the science mapping approach. The methodological tools used for this are:

- (1) the R-package *bibliometrix* (Aria & Cuccurullo, 2017) and
- (2) the analysis and visualization of network structures in VOSviewer (van Eck & Waltman, 2010), and the rendering of results in a VOSviewer-type visualization for complying with presentation schema across all network figures in this article.

Research Questions

The study goes from descriptive to interpretive level of inquiry and aims to answer four main RQs that form two broad stages of inquiry—one mapping the structure of literature reviewed and the other the conceptual aspects of the literature—that together cover aspects of structural and conceptual dimensions of the literature on VR/AR in science education:

- RQ1:** What were the trends of publishing in VR_AR in science education from 2006 to 2026 in terms of annual publications, countries, productive institutions, key journals and prolific authors?
- RQ2:** What publications and authors have had the highest intellectual impact on the field based on the number of citations and the co-citation networks?
- RQ3:** What thematic clusters and conceptual structures will be observed in the VR and AR research in science education based on keyword co-occurrence analysis?
- RQ4:** What shifts are observable in the research topics and technological focus during the time span being examined and what can the most recent research studies tell you about emerging trends?

From the bibliographic landscape (**RQ1-RQ2**) to the conceptual and temporal architecture of the field (**RQ3-RQ4**), the four questions aim to produce a descriptive orientation and an interpretative insight that can help researchers, science curriculum developers, and policymakers with their understanding of the field.

Data Collection

Because of its comprehensive scope of coverage of the most prevalent publications from peer-reviewed journals across the natural sciences, computer science, and educational technology, the three academic disciplines directly relevant to the assimilation of VR and AR research in science education, bibliographic information was taken from the well-known search engine Scopus (Elsevier). Data export was done in June 2026 to take a complete snapshot of publications at the time of analysis. In the case of VR and AR records, a single database design was deliberately selected by the designers over multi-databases designs due to the significant complexity of cross-database deduplication, reported in previous comparative database study (Mongeon & Paul-Hus, 2016), given:

- (1) inconsistent indexing of conference-derived journal extensions and
- (2) variable author-name disambiguation across IEEE Xplore, Web of Science and Scopus.

Restricting the records retrieved to those published in Scopus journals thus trade-maximal coverage of records for maximal internal consistency and citation reliability, as noted here and further discussed in the methodological limitations section.

Boolean search expressions were built and used with article titles, abstracts and author keywords. This query combined established technology-related terms with science-education-related terms to capture the intersection of immersive technology and science education contexts: KEYWORDS ("virtual reality" OR "augmented reality") AND KEYWORDS (Science education OR Science learning OR Science teaching).

Since the focus was on umbrella terms rather than similar terms or qualifiers, the terms "virtual reality," and "augmented reality" were search terms. Related search terms (e.g., MR, extended reality, and immersive VR) and related qualifiers (e.g., STEM education, chemistry education, and physics education) were excluded because of concern for precision and including unrelated search results. In the literature, MR and extended reality are used to refer to virtual and AR, respectively, as broad search terms. Broader search terms added noise to the search results by expanding the search to other topics beyond immersive technology. Related qualifiers were not used as search terms, since they would be covered under search terms "science education," "science learning," and "science teaching," and would result in search results that are more chemistry and physics centric over other less well-defined fields such as engineering and earth science. This is a limitation to the study (see methodological limitations) and future bibliometric studies in this area should attempt more search terms across multiple databases.

Records were systematically identified based on inclusion and exclusion criteria that ensured the retrieved records were relevant, quality and comparable. Of journals articles only those written in the English language and published in journals that were peer-reviewed and had citations were retained as these documents the substantively- examined and cited empirical and theoretical work which has entered the field in this particular domain. All conference papers, book chapters, and those published in languages other than English, were excluded, as is the case in similar bibliometric analyses of educational (Zawacki-Richter et al., 2019). After title and abstract screening, records were excluded if virtual/AR was mentioned and not the focus in the abstract, rather it was more of a peripheral topic, not related to science or STEM education.

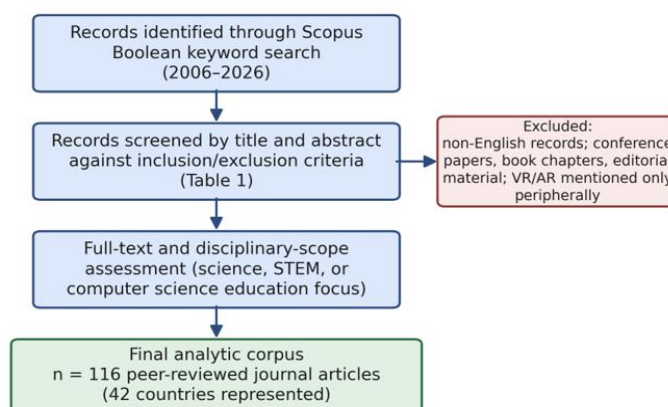
After the systematic search and the screening procedure, a total of 116 English language peer-reviewed journal articles were included in the final sample for analysis, between 2006 and 2026. The following bibliographic data was extracted and checked for each record that was retained: article title, complete author names, author affiliation, country of origin of author affiliation, publication year, source journal, author-assigned keywords, Scopus index keywords, abstract text, total number of citations listed in the Scopus at the time of data extraction, digital object identifier, and open access status. The exported fields were in comma separated value format and imported into R (version 4.3.2) using the *bibliometrix* package, for network analysis, imported in VOSviewer (version 1.6.20).

The retrieved corpus covers a geographically wide range of countries that contribute to the corpus, such that 42 national contexts are represented in the authors' affiliation. The overall trend of facilitating scholarly

Table 1. Inclusion and exclusion criteria applied in the data collection process

Category	Criterion	Decision/rationale
Inclusion criteria	Publication period: January 2006-June 2026	Aligns with the study's defined twenty-year temporal scope
	Document type: peer-reviewed journal article	Primary channel for original, citation-tracked scholarly contributions
	Language: English only	Ensures analytical uniformity and comparability across the corpus
	Subject: VR, AR, or mixed reality as a substantive focus of the study	Excludes studies referencing immersive technology only peripherally
	Disciplinary scope: science, STEM, or computer science education	Delimits the domain of inquiry to the intersection of immersive technology and science-related pedagogy
Exclusion criteria	Conference papers, book chapters, and editorial material	Excluded to maintain methodological consistency and citation reliability
	Non-English language publications	Precludes systematic cross-study comparison
	Studies referencing VR/AR without a science education focus	Removed following title and abstract screening

Note. Final analytical corpus: n = 116 peer-reviewed journal articles (2006-2026; English; Scopus; 42 countries represented)

**Figure 1.** Search and screening flow diagram for study selection (the authors' own elaboration)

communication in education without restriction of access, which is evident in the multiple open access routes in the educational technology research papers, in this corpus 65 articles per 116 (56.0%) were published as open access papers (UNESCO, 2023).

The identification, screening, and inclusion procedure summarized in [Table 1](#) is depicted graphically in [Figure 1](#).

Data Analysis

For analysis of the data, the sequence of method for bibliometric analysis recommended by Donthu et al. (2021) was followed, which involved performing a performance analysis and a science mapping. The two stages lay the groundwork to define the boundaries of the field quantitatively, and then to sketch the conceptual structure of the field by mapping it.

To address **RQ1** and **RQ2**, performance analysis was done. Frequency was computed for all the years from 2006 to 2026 in order to find patterns of growth and to see if there were bursts or drops in the volume of scholarly activity published in any given year. The country-level or institutional productivity was evaluated by splitting the affiliation field of each record and assigning the country to the end of each affiliation string. Author level productivity was measured in terms of number of appearances in the authorship field of all 116 records. Productivity and impact on the journal level were evaluated by raw publication numbers and by aggregate numbers of citations per citation source title.

Citation analysis was used to address **RQ2**. Scholarly influence of individual publications was determined using the total number of citations retrieved from Scopus and the corpus h-index was calculated according to the definition introduced by Hirsch (2005): h is the maximum value of the number of publications in the corpus that have at least h citations. The basic intellectual communities that are essential to the field were

determined by using co-citation analysis, which is based on the co-citations of the various publications and authors in the bibliographies of the 116 articles, in the VOSviewer software package, applying the methodology proposed first by Small (1973).

RQ3 and **RQ4** both used science mapping techniques to answer questions. To achieve optimal terminological coverage, author assigned keywords and Scopus-derived index keywords were merged using keyword co-occurrence analysis and a minimum occurrence threshold of three was used to ensure that the nodes have analytical value. Using van Eck and Waltman (2010) and Cobo et al. (2011), the resulting keyword network was clustered into thematic communities with the VOS clustering algorithm that was embedded in VOSviewer. Corpus segmentation was used in order to study the chronological evolution of thematic emphasis and three periods were defined: the assumption of an annual publication trend suggested by the visual ordering of the data, and qualitative assessment of the keywords profile that characterizes each of the periods was used to confirm this. All quantitative calculations were carried out using the R programming environment in the *bibliometrix* package, the network structures involved were calculated in the package VOSviewer and were validated parallel by the package *igraph* in R using the parallel analysis-methodology.

All three network visualizations presented in this article (co-authorship of countries, keyword co-occurrence and co-citation of authors) have been restructured as standardization of resolution, color palette and typography of all figures throughout the manuscript was essential for their presentation. The size of the nodes in these redrawn figures is strictly based on the empirical frequency or number of citations found in the corpus; the grouping of the nodes, and their color coding, reflect the clustering solution algorithm calculated from the input from the VOS clustering algorithm in VOSviewer. The thickness of the edges between the figures in “edge thickness” view represents relative strength of connections within each cluster and should not be interpreted as exact pixel-for-pixel correspondences of the normalized connection strength values of VOSviewer but should be evaluated by the reader against the underlying association strength values indicated in VOSviewer output files (available from the corresponding author upon demand).

Methodological Limitations

There are several limitations in this study's methodology that do not impact the validity of the findings but may impact their interpretation. The first is that analyses were limited to Scopus-indexed literature and thus works indexed only in Web of Science or IEEE Xplore are excluded; such literature might be disproportionately computer-science-heavy in its focus on VR/AR, and a multi-database analysis would be a logical continuation. The second limitation is that the corpus was limited to journal articles, not including the conference proceedings (e.g., IEEE VR, IEEE ISMAR, and ACM CHI), which often contain the timeliest engineering-oriented literature on markerless AR tracking, mixed-reality interaction design, and HMD optimization; this synthesis should be complemented by a review of the conference literature to identify the most current developments. The third limitation is that the citation counts are subject to a recency bias: articles published closer to the data extraction date have had less time to accrue citations, which may deflate the impact scores of the most recent works. The fourth limitation is that the country and institution assignments were based on parsing the last element of the Scopus affiliation strings, a heuristic that may misinterpret nonstandard conventions; likewise, the decision to classify each article's dominant technological modality (VR, AR, or MR) involved interpretive judgment in cases of meaningful multiple coverage. The fifth limitation concerns the search strategy: because discipline-specific keywords (e.g., physics education, chemistry education, and biology education) were deliberately excluded in favor of umbrella terms, studies that frame themselves solely in single-discipline terms could not be retrieved, which naturally restricted the corpus to 116 records; the findings should therefore be read as describing the subset of VR and AR research that explicitly identifies itself with science education, and future studies could extend the query with discipline-specific terms to test how far they generalize. Finally, the co-citation and co-authorship network diagrams are dependent on the clustering threshold and layout algorithm in VOSviewer, and different thresholds could produce different network structures; the clusters presented here should be regarded as one possible way of organizing this information, rather than an objective classification of the field.

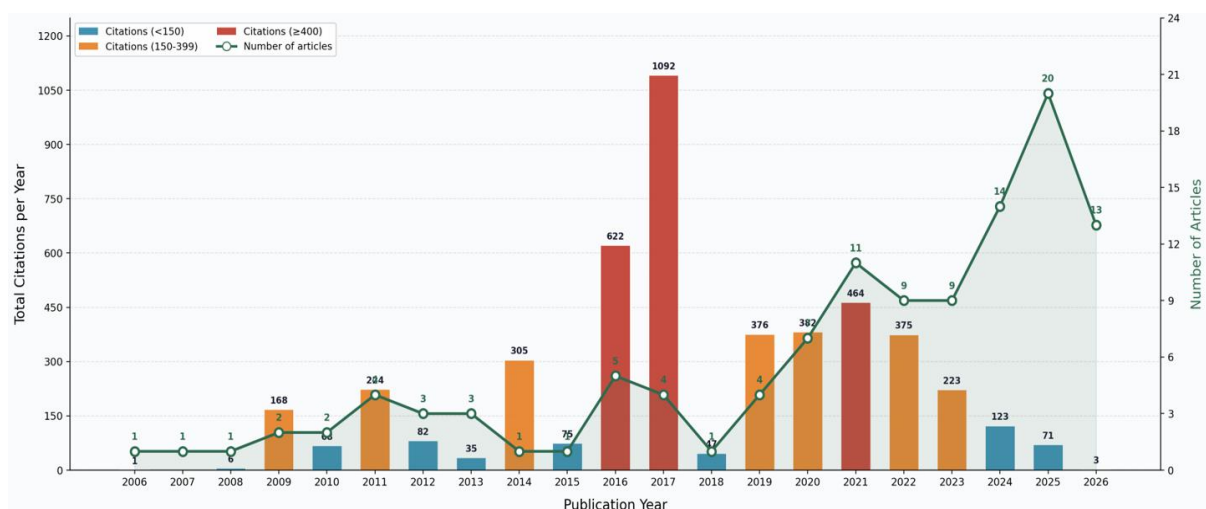


Figure 2. Annual publication count and total citations per year for VR and AR in science education journal articles (the authors' own elaboration)

RESULTS

The results of the bibliometric analysis are presented below for every RQ that guided the study. The data-supported analysis analyzed 116 peer-reviewed journal articles published in the field of VR and AR in science education from Scopus (2006-2026).

Publication Trends, Productivity, and Structural Characteristics (RQ1)

The number of articles published per year and the number of citations counted for every annual cohort on the study period are plotted in [Figure 2](#) to clearly show an accelerating trend in annual publication output. Prior to 2009, there were only scattered publications in the field, appearing in 2006, 2007, and 2008. The first wave of citation impact was seen with the 2009 cohort, which had two articles that, combined together, received 168 citations, including the seminal and influential study by Arvanitis et al. (2009) on mobile AR. The number of articles in the period from the early 2010's through 2015 was also relatively small, averaging from one to four articles per year, but two specific publications from the final two years of this period, namely Johnson-Glenberg et al. (2014) and Lindgren et al. (2016), were later among the most cited in the entire corpus.

The corpus began to grow in volume starting in 2016, and 2017 saw the largest number of publications along with 1,092 citations—substantially generated by Moro et al. (2017), the most influential article in the dataset that year. Output continued to rise into the early 2020s; during the COVID-19 pandemic (2020-2022), when access to physical laboratories was often limited, production held steady at seven to 11 articles per year. The larger number of articles on record in the most recent years (2024 – 14 articles, 2025 – 20 articles) is a sign of the rapid growth of VR and AR researches in the field of science education, rather than reaching maturity and settling in a plateau. The relatively low number of citations for the newest cohorts (2024-2026) is a result of the consistent “recency” effect that is typical in citation-based bibliometric metrics, which can be applied to determine the number of citations a publication receives for a specific period within a year.

Based on where the researchers who wrote the articles were affiliated in the world, one can see that VR and AR research in science education is substantial and far-reaching internationally ([Figure 3](#)). By far the most productive national context was United States, with 78 affiliation-level instances, three times more than the second ranked country. Australia ($n = 25$) and China ($n = 22$) were the next two most productive contexts, followed by Greece ($n = 17$) and Taiwan ($n = 15$) as the fifth and sixth most prolific countries. There were 11 to 13 cases of affiliation in Germany, Spain and Turkey, and other countries in the second tier of moderately active countries brought between six and nine cases (some including Denmark, Norway, Malaysia, United Kingdom). The presence of a strong output focus in the United States may be due in part to the higher levels of institutional investments in research infrastructure for immersive technologies among universities in the United States, as well as the historical grounding of headquartered institutions for embodied cognition and presence research among North American departments of educational psychology.

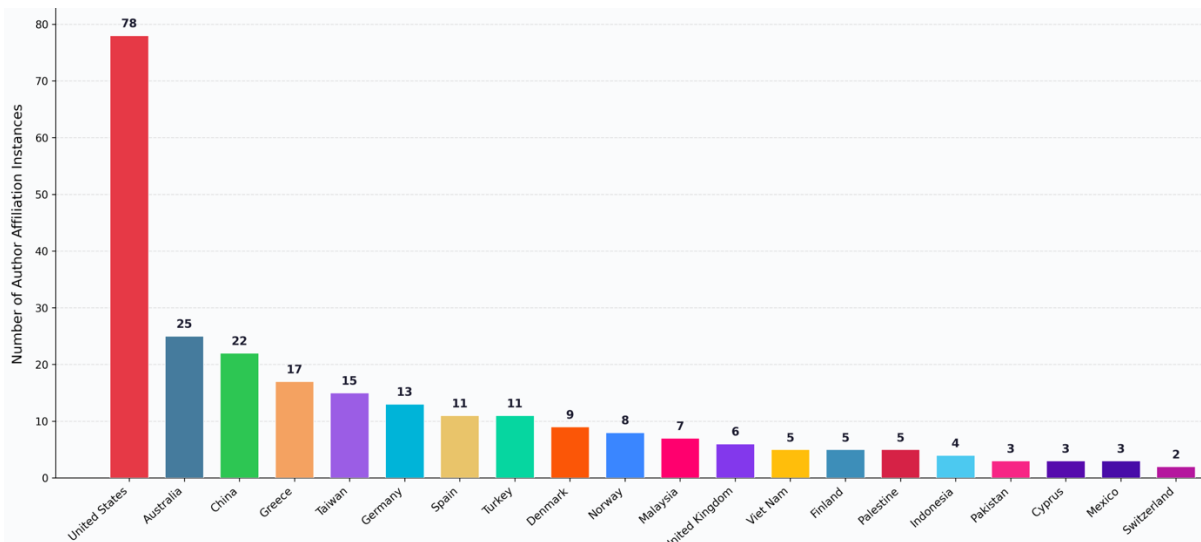


Figure 3. Top 20 contributing countries by author affiliation count (the authors' own elaboration)

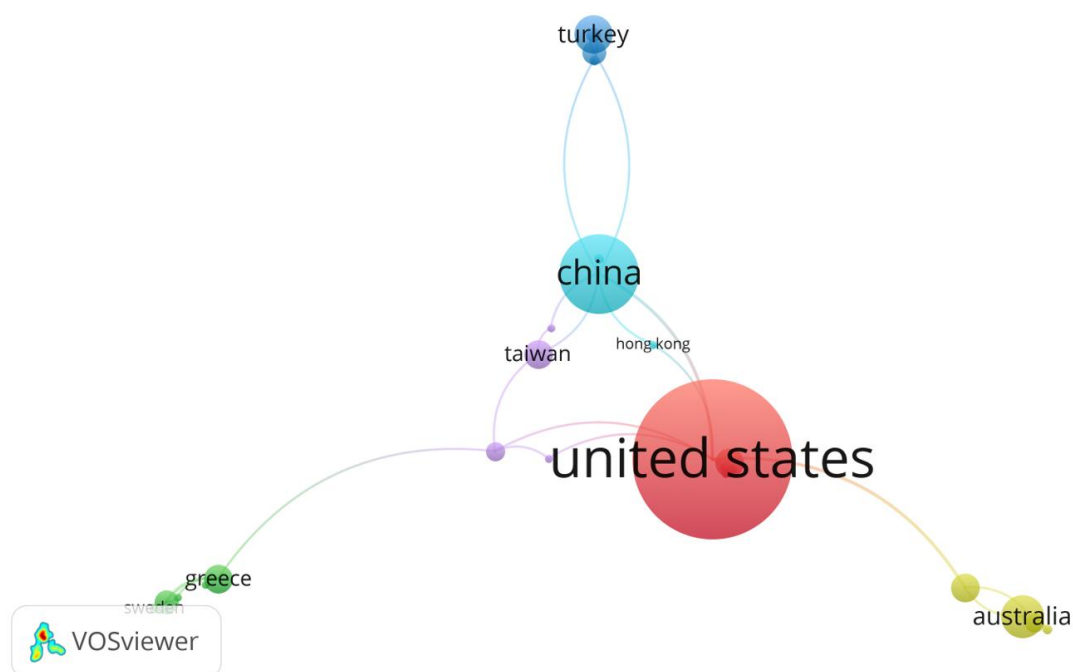


Figure 4. VOSviewer co-authorship network of countries, VR and AR in science education (the authors' own elaboration)

The co-authorship graph of countries from the VOSviewer (**Figure 4**) shows a moderately interconnected international collaboration graph. It can be distinguished in five clusters, the blue cluster contains United States, Taiwan, United Kingdom, and United Arab Emirates, representing the largest and most far-reaching of the collaborative hubs, with a strong trans-continental collaborative tradition; the red cluster contains Turkey, Indonesia, Luxembourg, France, Jordan, emphasizing a global Middle-Eastern and European collaborative tradition; the yellow-green cluster contains Greece, Cyprus, Palestine, and Finland, representing a global linkage and tradition in collaborative work based in the Mediterranean region and the North; the orange cluster contains Denmark and Australia, reflecting a shared research partnership between the two countries despite their geographic distance; the green cluster contains Spain and South Africa, representing the trans-continental partnership with special links to science education reform in the Mediterranean region. The network has no central leader, except for the US which has highest total link strength and is the main cross-cluster connector, and the Indonesia and Turkey nodes, which have rather high intra-cluster densities for a fairly small corpus contribution count.

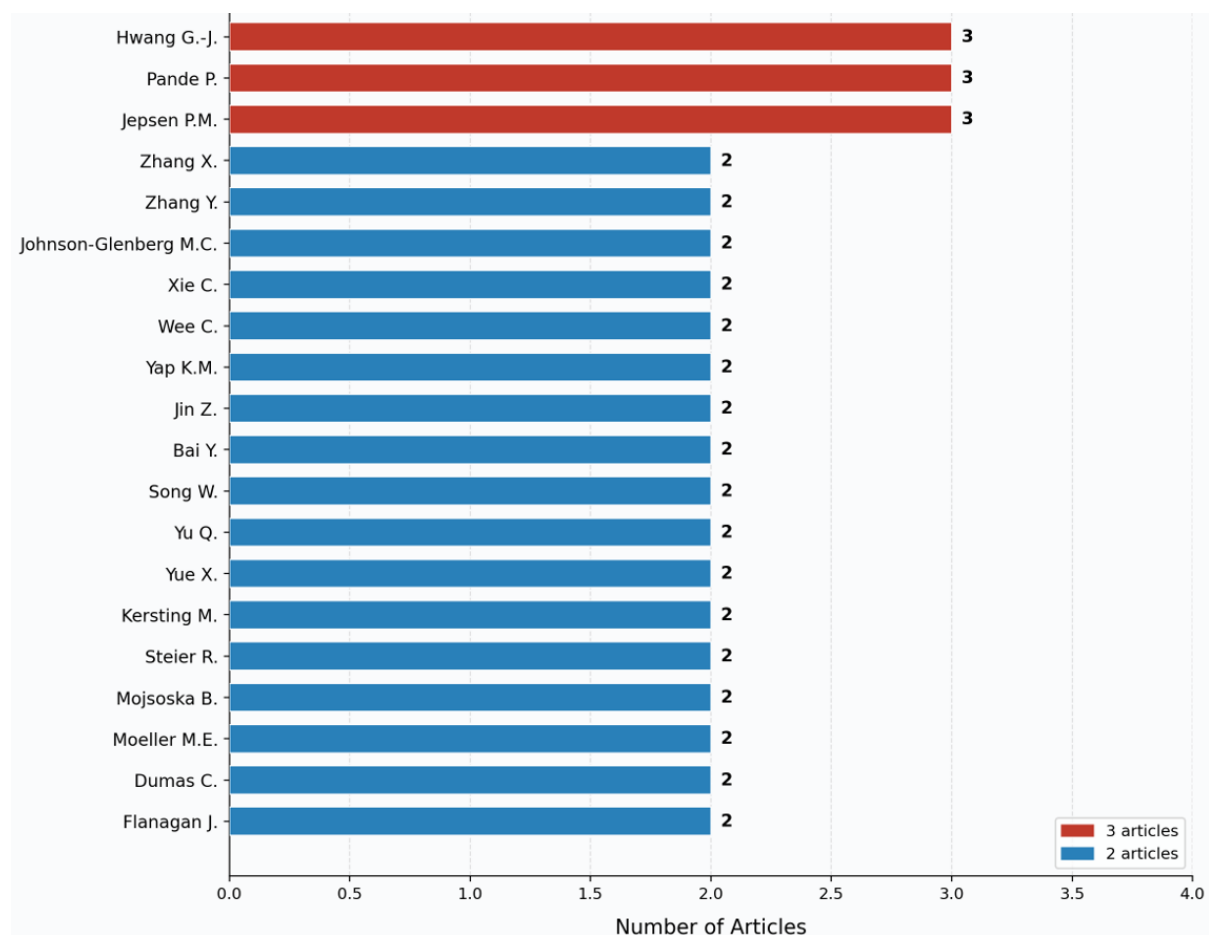


Figure 5. Top 20 most prolific authors in the VR and AR in science education corpus (the authors' own elaboration)

An author-level productivity analysis (Figure 5) revealed that the three authors with the most articles in the corpus were Hwang, G.-J., Pande, P., and Jepsen, P. M. A further group of authors, including Zhang, X., Zhang, Y., Johnson-Glenberg, M. C., Xie, C., Wee, C., Yap, K. M., Jin, Z., and Bai, Y., each authored two articles. The tight cluster of the authors' names Pande, P., Jepsen, P. M., Mojsoska, B., Moeller, M. E. shows an enduring longitudinal research program on the role of immersed VR simulations in localizing learning in undergraduate science education (Pande et al., 2021) that was rare in this corpus.

Journal-level analysis (Figure 6) revealed that Computers and Education ($n = 6$ articles), Journal of Science Education and Technology ($n = 5$), a group of four journals with four articles each namely Computers and Education: X Reality, Education and Information Technologies, and IEEE Transactions on Learning Technologies were the most productive single source. Remarkable also is the existence of Computers and Education: X Reality as a separate (if moderate and productive) venue for publication because the increasing number of research articles in the field of immersive technology in teaching and learning indicate its maturity as a subdiscipline that deserves its own publication structure. The remaining articles were spread among 70 other distinct journals, reflecting the high level of diversity among academic journals besides the top journals.

Publication patterns (Figure 7) show that of the 116 articles, 65 (56.0%) had been published under some kind of open access license at the time the data was extracted. Gold open access/hybrid gold open access were the most plentiful subcategories ($n = 10$, 8.6% of the full corpus and $n = 14$, 12.1% of the full corpus, respectively). The combinations of gold open access and green open access were the most numerous subcategories, respectively $n = 19$ (16.4% of full corpus) and $n = 16$ (12.1% of full corpus). The other 51 articles (44.0%) were obtained only with the help of institutional and/or commercial subscription services, a percentage that is broadly equivalent to the percentage of open access articles observed in similar educational technology bibliometric data sets (UNESCO, 2023).

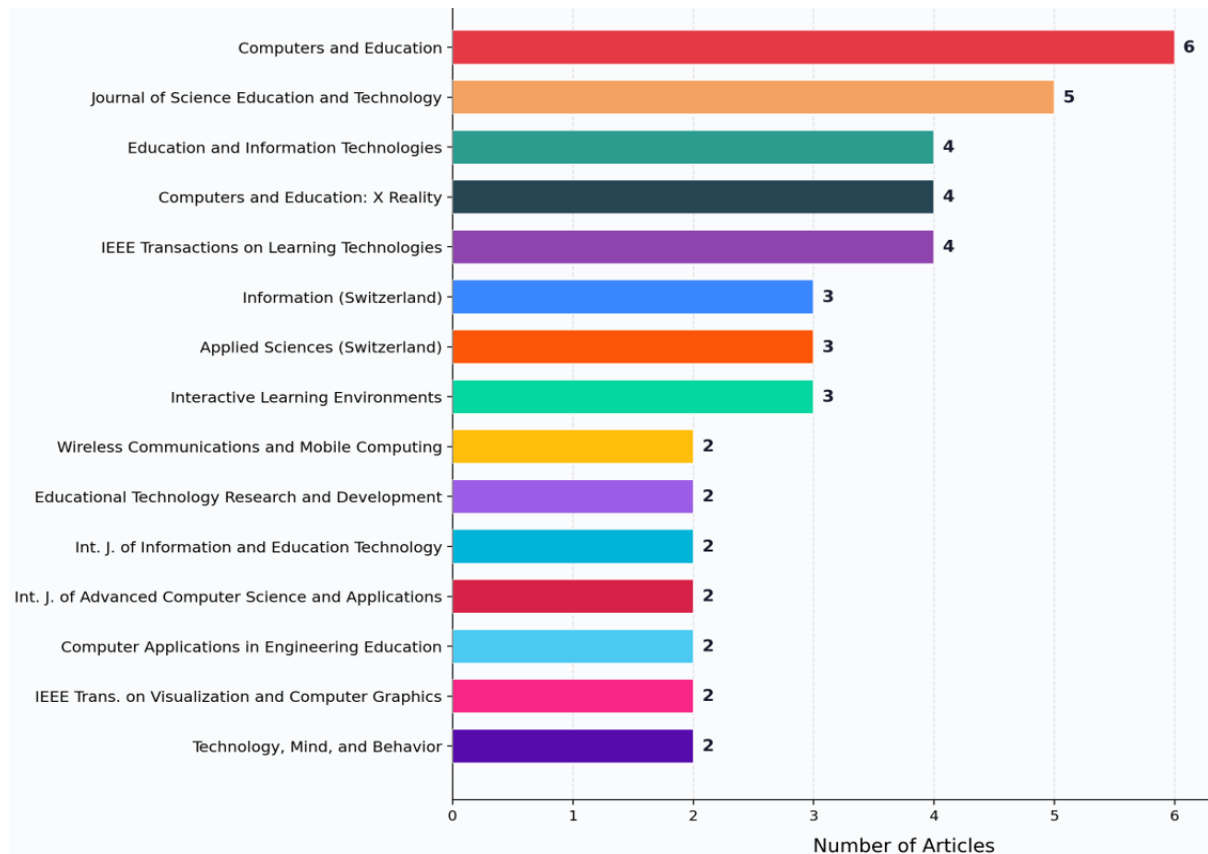


Figure 6. Top 15 source journals by number of articles published (the authors' own elaboration)

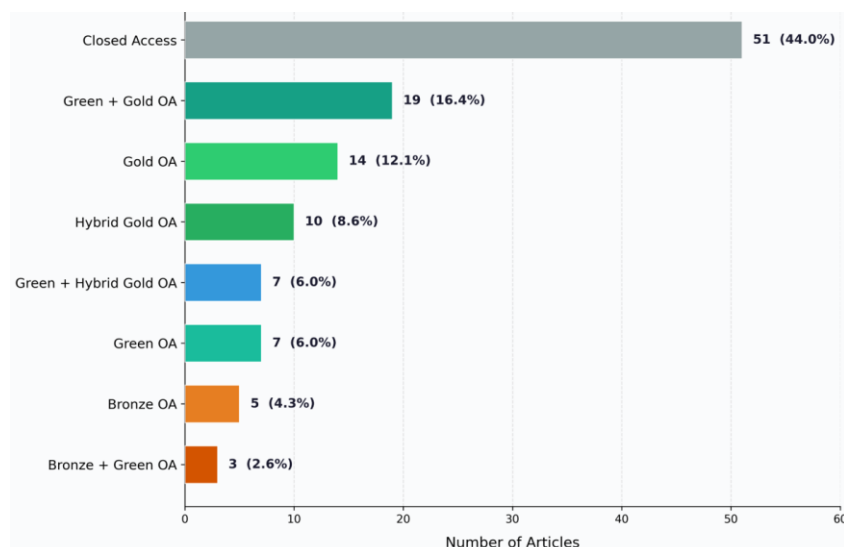


Figure 7. Distribution of open access status across the VR and AR in science education corpus (the authors' own elaboration)

Citation Impact and Intellectual Influence (RQ2)

In total over the 116 papers, the number of citations were 4742 with a mean of 40.88 citations per paper (median = 10.0, standard deviation = 99.43, maximum = 842). The corpus h-index was 33, so 33 articles had 33 or more citations and shows that the field of education technology is quite sophisticated and influential within the field of education. It has the characteristics of bibliometric data, which is evident by the citation distribution (a strong right skew in the data, virtually all citations at the "nubs," with a small number of very influential articles garnering a large amount of hits).

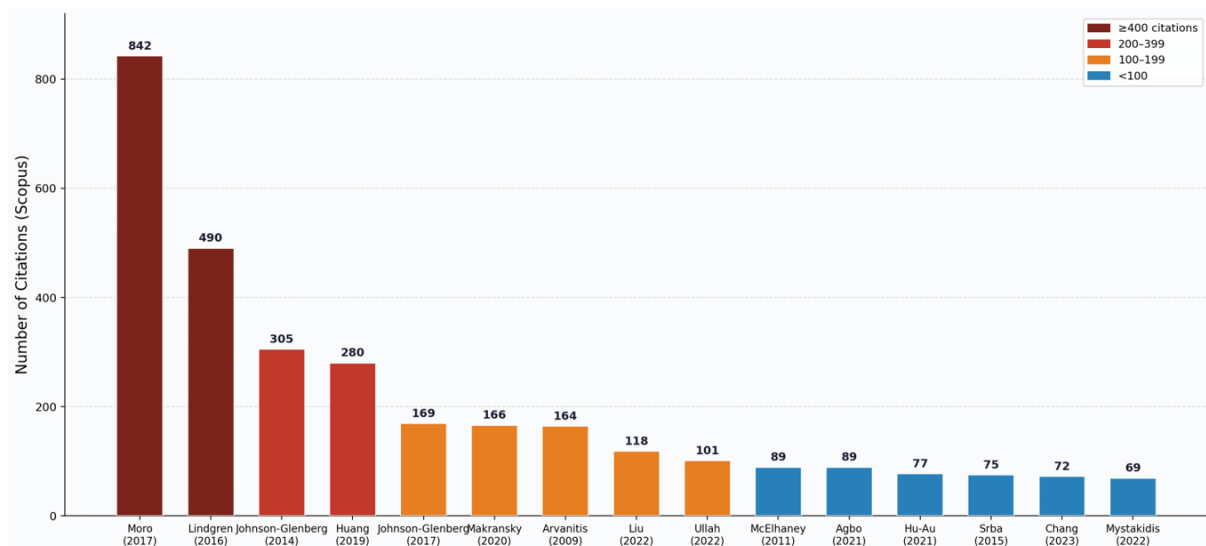


Figure 8. Top 15 most-cited journal articles in the VR and AR in science education corpus (the authors' own elaboration)

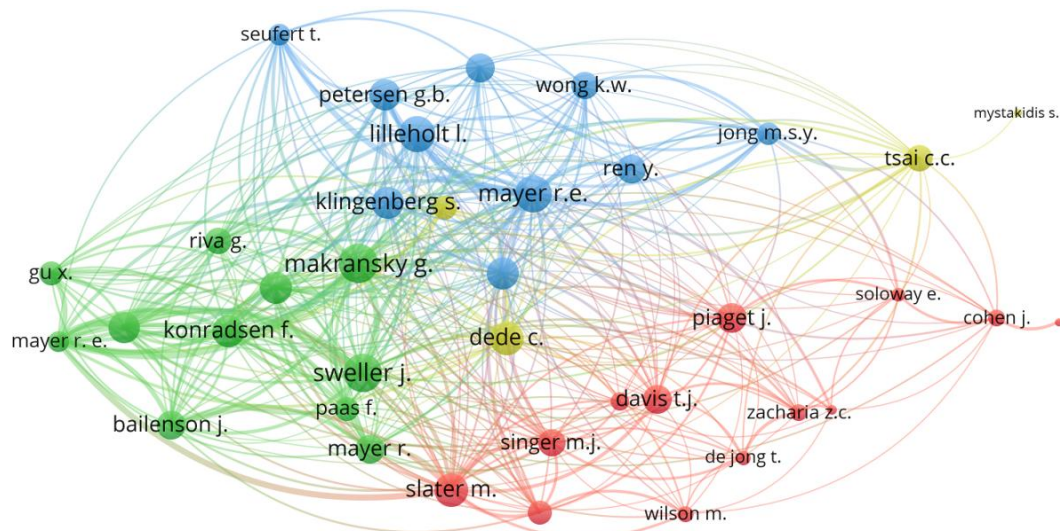


Figure 9. VOSviewer co-citation network of cited authors, VR, and AR in science education (the authors' own elaboration)

The publication with the highest number of citations (842) in the corpus was Moro et al. (2017) compared to the effectiveness of virtual and AR in health sciences and medical anatomy education, which is much more than any other publication in the corpus (Figure 8).

Lindgren et al. (2016) followed with 490 citations for its foundational research of embodied interaction in the context of MR planetary motion simulations, and Johnson-Glenberg et al. (2014) had 305 citations for their study of collaborative embodied learning in a MR, motion capture, classroom environment. Huang et al. (2019) ranked as the 4th most cited with 280 citations, and Johnson-Glenberg and Megowan-Romanowicz (2017) ranked 5th with 169 citations. These five most-cited articles amount to 44.0% of the total number of citations on the corpus, reflecting a tendency toward a highly polarized intellectual influence from a restricted group of landmark articles.

Four basic intellectual communities are identified through the co-citation analysis of cited authors (Figure 9). The large green cluster, shown in green and anchored by the work of Bailenson, J., Riva, G., Gu, X., Makranksy, G., and Konradsen, F., represents the immersive VR and cognitive load tradition, which traces its theoretical lineage to presence theory, multimedia learning theory, and Mayer's generative theory of multimedia learning. The second blue cluster, around Lilleholt, L., Klingenberg, S., Petersen, G. B., and Mayer,

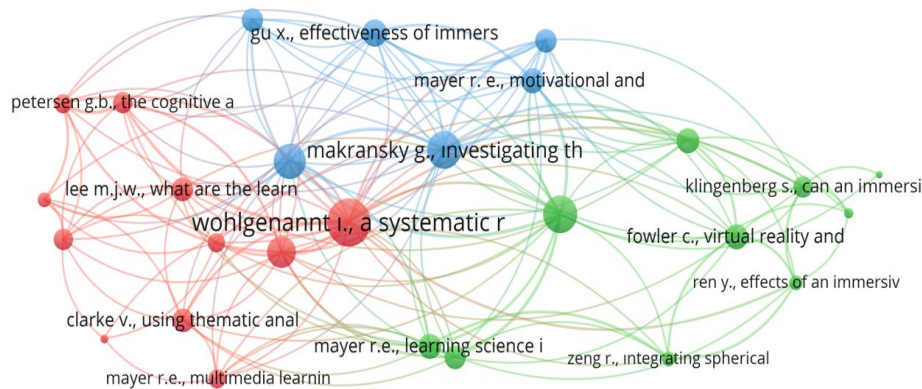


Figure 10. VOSviewer co-citation network of cited references, VR and AR in science education (the authors' own elaboration)

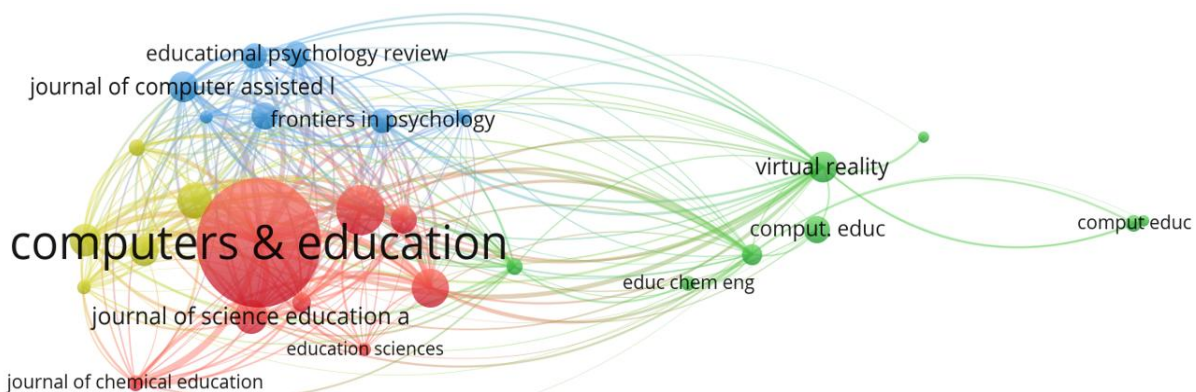


Figure 11. VOSviewer co-citation network of cited sources (journals) (the authors' own elaboration)

R. E. (as a separate node from the green cluster), Wong, K. W., and Jong, M. S. Y., is a cluster on immersive learning that is effective in science, with strong Scandinavian and Asian contributions. The third red cluster is grounded in the VE and educational simulations tradition of Davis, T. J., Slater, M., Singer, M. J., and De Jong, T., which bridges the gap between computer science basics and science lab research. The fourth yellow cluster is centered on Tsai, C. C., Piaget, J., and Dede, C., each having an epistemology of constructivism and science learning, placing immersive technology in the context of the theories of constructivist and science learning. Central and widespread occurrence of Sweller, J. and Paas, F. throughout all four clusters provides further evidence that cognitive load theory is a cross-colligative theory in the corpus.

Figure 10 depicts the field's intellectual structure at the publication level through the co-citation analysis of cited references. The analysis shows a segmented research field in which the design space of immersive learning is the most central, relating to the cognitive and emotional design of immersive science learning environments (Makransky et al., 2020). The red cluster is anchored by the systematic review of Wohlgenannt, I. and includes Petersen, G. B., Lee, M. J. W., and Clarke, V., whose works represent the tradition of systematic reviews and qualitative syntheses. A blue cluster is anchored by Makransky, G., Gu, X., and Mayer, R.E., capturing the experimental-effectiveness tradition in immersive learning research. A further green cluster, anchored by Klingenberg, S. and including Fowler, C., Ren, Y., and Zeng, R., represents the applied VR-in-science effectiveness tradition that is most closely aligned with the present study's focus.

Figure 11 displays a source-level co-citation network that shows the relationship among the 116 corpus articles as citing documents. The most influential source journal in the intellectual bedrock of the field is *Computers and Education*, as is demonstrated by its large size and strong overall linkages of its nodes. The science education and educational technology mainstream consists of a large red cluster, with the journal of science education and technology, *Computers and Education*, and *Journal of Chemical Education*, *Education Sciences*. *Educational Psychology Review*, *Journal of Computer Assisted Learning* and *Frontiers in Psychology* are supported by a smaller blue cluster, which stands for the psychological mechanism and cognitive science

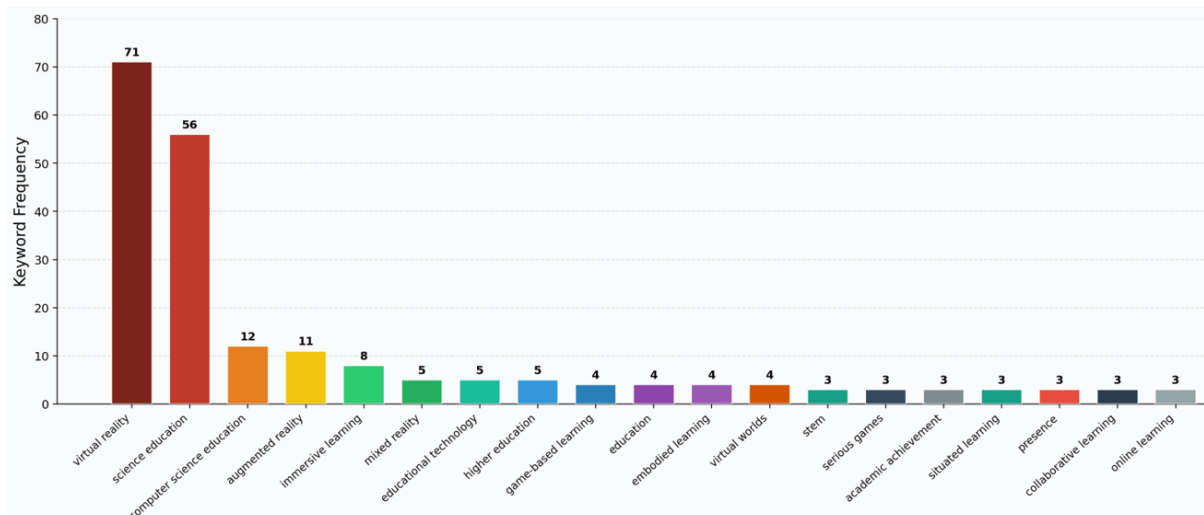


Figure 12. Top 19 author keywords by frequency in the VR and AR in science education corpus (the authors' own elaboration)

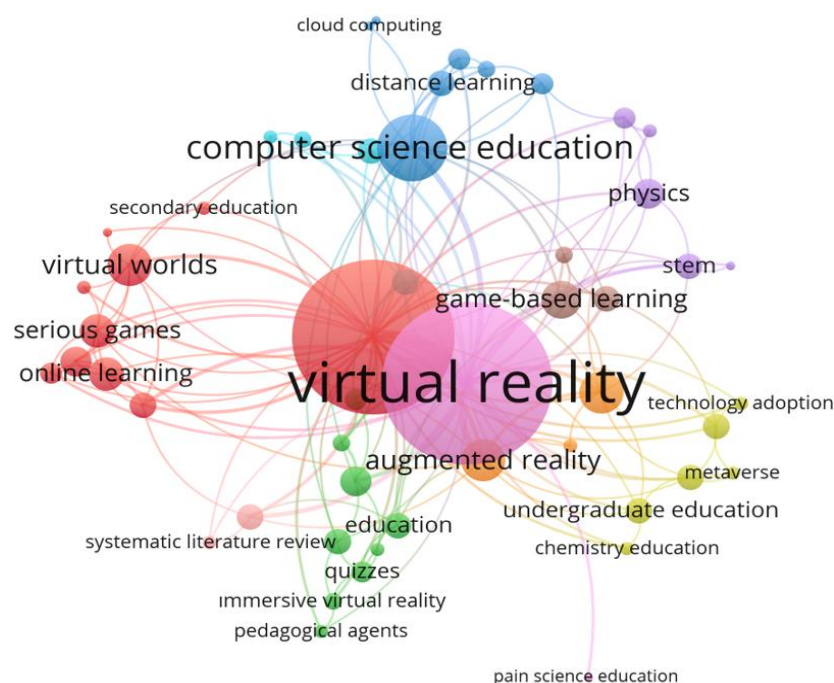


Figure 13. VOSviewer keyword co-occurrence network, VR and AR in science education (the authors' own elaboration)

tradition. The venue cluster for technology forward, discipline specific is a separate green cluster which includes Virtual Reality (journal), Computers and Education: X Reality, and Education for Chemical Engineers. When looking at the co-citation network between the two bodies, it can be observed that they have the tightest link ties with each other, which establishes for the researchers both of them as the two most relevant anchor points when they cite the literature of this domain.

Thematic Clusters and Conceptual Structure (RQ3)

A total of 116 articles were analyzed using keyword co-occurrence and resulted in a network with four main thematic communities (Figure 12 and Figure 13). The author keyword frequencies were analyzed, the results showing that the terms VR ($n = 71$) and science education ($n = 56$) are highly dominant, forming the core concept axis of the corpus. Computer science education came in third ($n = 12$); followed by AR ($n = 11$); immersive learning ($n = 8$); MR ($n = 5$); educational technology ($n = 5$) and higher education ($n = 5$).

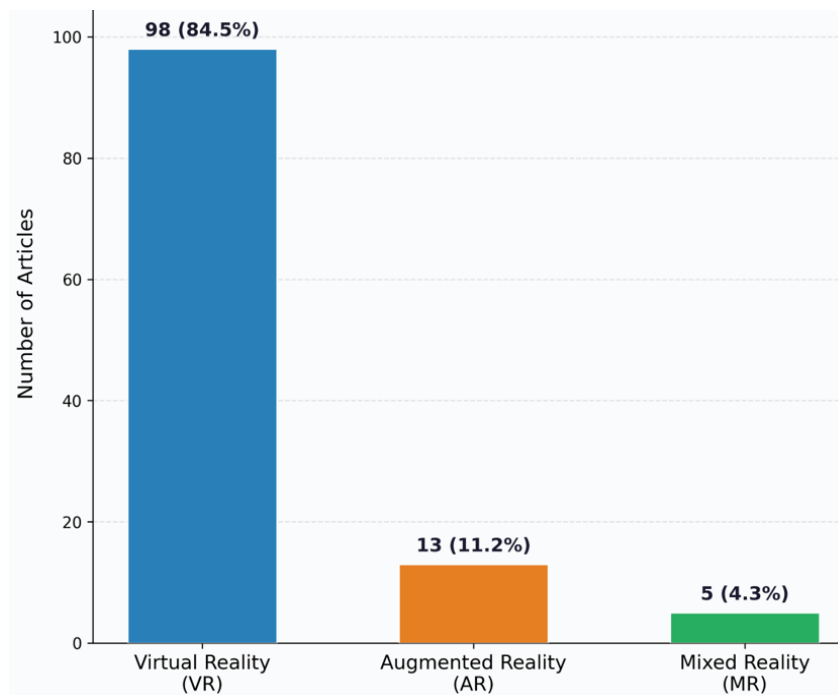


Figure 14. Distribution of primary technological modality across the VR and AR in science education corpus (the authors' own elaboration)

The VOSviewer keyword co-occurrence network (see [Figure 13](#)) shows a more detailed thematic structure beyond that only provided by the frequency bar chart. The biggest and most pivotal cluster is the virtual immersive learning environments cluster (red/pink) where VR is central, and includes virtual worlds, serious games, game-based learning, online learning and secondary education—a cluster representative of the immersive learning environments that concern the use of virtual technology in formal and informal science learning environments. There exists another cluster (magenta/pink): here the main nodes are game-based learning and AR, both linked with education and systematic literature review, which represents the tradition of methodological synthesis and AR specific applications. There is also a third major blue cluster supporting computer science education and it covers distance learning, cloud computing, physics and STEM; the cluster is called the cluster of computational and disciplinary science education. A few exemplary works in this cluster include those of Gercek et al. (2016) who created cloud-based virtual computer network (VLabs) laboratories for online engineering education, Ruiz-Martínez et al. (2013) who developed a virtualization tool for teaching students advanced concepts in computer networking, and Takala et al. (2016) who used a longitudinal capstone course to enable students to design their own VR applications, showing how the computer science education cluster extends beyond computer programming or technology consumer education. Wee et al. (2022) similarly designed a virtual reality environment (iProgVR) to improve introductory programming learning, and Zhao et al. (2022) applied virtualization technology to cultivate engineering innovation ability among applied undergraduates. The emerging technology futures and higher education context group were represented by a fourth yellow-green cluster, combining metaverse, technology adoption, undergraduate education, and chemistry education. Instructional design variables that directly correspond to pedagogical aspects play important roles in establishing conceptual bridges between the major thematic communities identified in the network, such as immersive VR, pedagogical agents, and quizzes, as highlighted in the green inter-cluster zone.

A complementary technological analysis of the modality that is highlighted in each article ([Figure 14](#)) shows an overwhelming orientation of the articles towards VR as the main focus of technological research, with 98 articles (84.5%) focused on VR applications, 13 articles (11.2%) focusing mainly on AR, and five articles (4.3%) primarily on MR. On the one hand, this variant is caused by the general maturity of VR hardware and software over and against AR/MR but also by the fact that the integration of VR head mounted display technology into the formal research infrastructure in education is much older than software for mobile AR.

Temporal Evolution and Geographic Research Trajectories (RQ4)

The analysis of the evolution of the themes in the period of 20 years can identify three stages of development. The first phase (2006-2013) was articulated by low, but well-building, scientific research output, notably Arvanitis et al. (2009), and Kennedy-Clark (2011), who set the empirical and theoretical base for immersive science education research. The research that took place in this phase focused mainly on issues of accessibility and feasibility, that is, whether the immersive technology could be appropriately used in real classroom and informal learning environments, as well as whether it could benefit learners with different needs such as physical handicaps who used mobile AR applications (Arvanitis et al., 2009).

The second phase (2014-2019) is the theoretical consolidation phase of the field, where the two over-dominating traditions in the co-citation network consolidated, namely the embodied cognition and the presence theory. The four most-cited articles in the entire corpus were written over this six-year period (see Huang et al., 2019; Johnson-Glenberg & Megowan-Romanowicz, 2017; Johnson-Glenberg et al., 2014; Lindgren et al., 2016; Moro et al., 2017). Literature published in these landmark publications is clustered into a comparatively narrow period of time (between 2014 and 2019), indicating that this time can be considered a critical formative period that witnessed key theoretical conceptions of the field and empirical research benchmarks, laying a foundation for later research that builds on, replications, or extends foundational literature.

The third and present one (2020-2026) is marked by an accelerating volume, a growing methodological variety, and the beginning of new technology and pedagogy themes. There is emerging interest in immersive remote science instruction during the COVID-19 pandemic (2020-2022) as science attempts to reconstruct pedagogical practice within a VE for teaching and learning when in-person access to science laboratories is limited (Makransky et al., 2020; and a proliferation of studies that followed). In the case of biomedical laboratory science, VR games developed by Frøland et al. (2020) were used to sustain our pedagogic efforts with science laboratory instruction where access to the physical laboratory was not possible, whereas the technology-mediated transformation of an entire doctoral summer school developed by Cullinane et al. (2022) was a direct institutional response to the pandemic-related restrictions, highlighting how the disruption has sparked innovation in the fields of K-12 and graduate-level science education at the same time. The last few years (2023-2026) fit with a slightly different focus, as the literature begins to turn the corner towards computational thinking and programming education in VR environments (Parmar et al., 2023), the addition of digital literacy frameworks to VR, AR, and MR applications (Chang et al., 2023), and increased evidence of the long-term and longitudinal effectiveness of VR and AR environments (Pande et al., 2021), a topic that was absent or marginalized during the earlier phases of development of the field. This significant rise in the number of publications for the last two years, despite relatively small citations, is indicative of an era of rapid growth in field, not saturation in terms of themes, and suggests substantial opportunities for future theoretical and empirical input.

Besides the co-authorship analysis, the bibliographic coupling network between countries (**Figure 15**) provides insight into the countries with the greatest overlap in reference sets: that measure is intelligently co-authorship, not direct collaboration. These five distinct communities emerge: a blue cluster around the United States, Taiwan and the United Kingdom with the widest common reference foundation, and a red cluster around Turkey, Indonesia, Luxembourg, France and Jordan, united by their common interest in pedagogical applications and educational technology frameworks, a yellow-green cluster around Greece, Cyprus, Palestine, Finland and Oman, linked by a shared Mediterranean and cross-regional science education reform discourse, an orange cluster around Denmark and Australia, with their coupled bibliographies reflecting a common engagement with Scandinavian immersive learning research, and a green cluster around Spain and South Africa, united by a similar coupling in their common science-education reform interests in technology and equity in resource-varying learning contexts. The United States node is at the highest level of centrality in each of the five clusters, reinforcing the role of North American research output as the main shared body of reference for the field in general by all major national research communities. Xie and Lee (2012) likewise contributed an early visual approach to nanotechnology education.

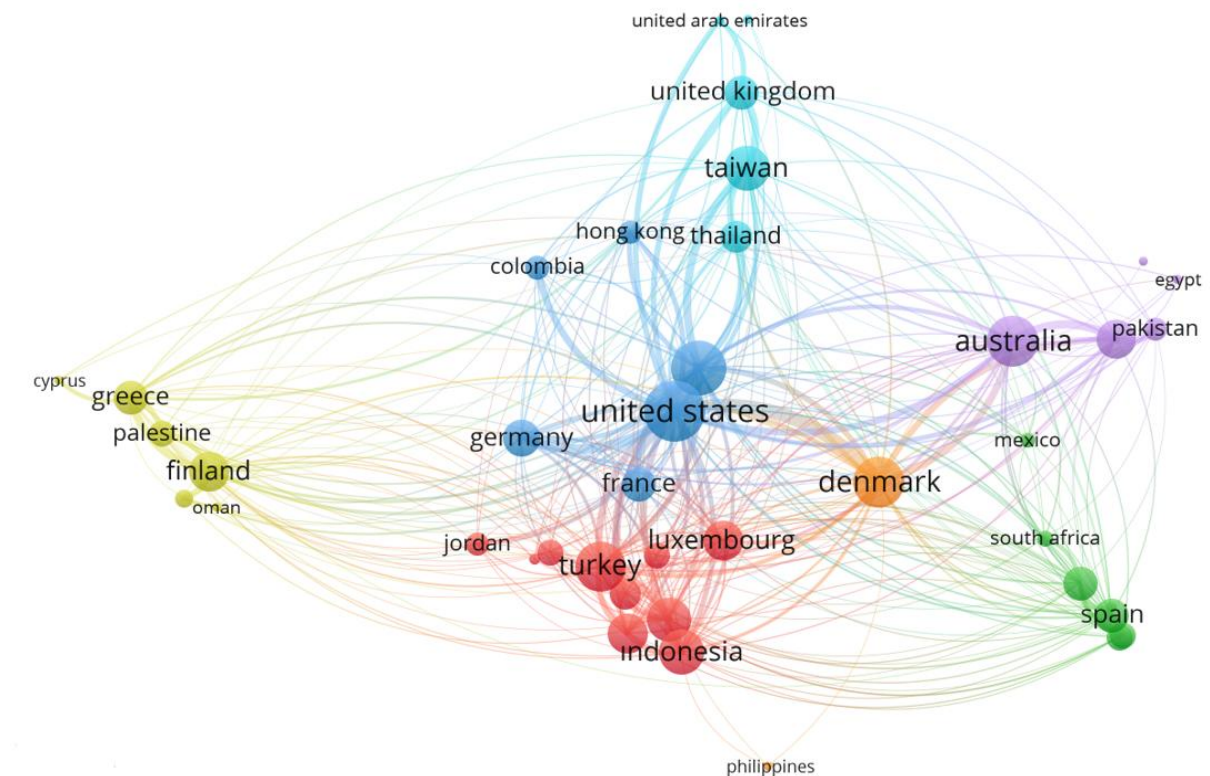


Figure 15. VOSviewer bibliographic coupling network of countries, VR and AR in science education (the authors' own elaboration)

DISCUSSION

As shown in this study, the prose that has appeared each year in this field can be seen to have advanced along a distinct path in the last 20 years. The limited and intermittent yield of the pre-2014 era is coherent with an emerging niche technological research field in which immersive hardware was still expensive, very limited and largely out of the reach of mainstream educational research. The speed with which this surge took place, particularly beginning in 2016, continued through the COVID-19 years, and is then expected to have peaked in 2024 and 2025, reveals a pattern of fast disciplinary growth, rather than coming to a steady state. Although this is somewhat at odds with that which is often seen in other educational technology sub fields, this pattern is typically accompanied by leveling off after a certain point after the basic questions in the theory have been explored sufficiently (Zawacki-Richter et al., 2019). The continued surge of papers found here points toward a research trajectory that may be expected to continue into future—one that still appears to be in a state of active expansion, and likely being fueled by further reductions in the cost of VR/AR technology, rising institutional infrastructure (Marques et al., 2024) and increasing growing pains from the many new technological variations that have come along since, such as MR and metaverse learning platforms, that create new RQs to be solved over and above overt issues of basic technological feasibility that we've seen overcome in Science Education these past few years.

As evidenced by the corpus h-index of 33 and the mean number of citations per article (40.88), these numbers demonstrate a relatively mature and influential field, far higher than those normally found for similar sized bibliometric corpora in the relatively new and still developing field of educational technology. This may be due to two factors: First, VR/AR research is truly interdisciplinary and appeals to authors citing broadly—namely in medicine/health professions education as well as in computer science, educational psychology, and instructional design, as well as physical education (Meng, 2021). Second, the relevance of papers such as Moro et al. (2017) extends well beyond science education and impacts on medical/health professions education as a whole, meaning they may have disproportionate and more general intellectual impact.

One of the findings of this analysis that stands out is the extreme share of the affiliation in the United States where more than 3 times as many affiliation instances are found as in the second most prolific country, Australia ($n = 25$). This concentration may arguably be indicative of the convergence of significant institutional research investment on infrastructure for immersive technologies, of the historical presence of embodied cognition and presence theory in the program of the department of educational psychology and cognitive science in the United States, but also, and especially, of the early availability of consumer VR hardware in North American markets. While Australia, China and Taiwan are under-represented, the support of these important countries and others from around the world, particularly the East Asian and Oceanian research communities, suggests that it has nevertheless made good headway towards meaningful international diversification, outside of North America and Europe.

Despite the relatively connected co-authorship network discovered in this study, which shows identifying sub-regional clusters in Scandinavia and in the Mediterranean, as well as a central position for the United States, the overall structure of collaborative partnerships may be more tightly knit than has been often claimed in similar educational technology related bibliometric studies. This somewhat positive cooperation dynamic can be attributed to not only the large technical infrastructure requirements for immersive technology research, which could encourage multi-institutional and multinational projects to jointly provide an expensive technical infrastructure and hire specialized technical personnel and software development to support them, but also to the fact that rarely does a single institution have the necessary funds to invest in such projects.

The common themes that emerge from both the co-citation and keyword analyses illustrate a shared “theoretical texture” of the field that is based in a significant way on three overlapping and interlocking theoretical traditions: Embodiment-awareness theory, the presence theory, and situated learning theory. The top three papers (Johnson-Glenberg et al., 2014; Lindgren et al., 2016) in the rank list of co-citations clearly show that the theoretical framework that is dominant in the field is the idea of embodiment – that abstract scientific knowledge is meaningfully grounded by physical movement or gesture. Findings from studies that directly compare the immersive (VR) and non-immersive (NVR) instructional experiences, such as that documented by Çakıroğlu et al. (2021) in which the VR environment was used to compare the immediate learning experiences resulting from the presentation of the same topic of human anatomy to a conventional program (NVR) that merely presented the material in the form of a conventional animation-based experience, provide converging support for the theoretical premise that immersion alone, rather than a mere presentation of the material with multimedia, is responsible for the learning benefits evident in this direct comparison. This convergence has resulted in a vast amount of research that is united in its main findings, but there is a persistent discussion about the relative neglect of other theoretical perspectives (e.g., cognitive load theory and self-determination theory) that could be relevant to the motivation and cognition involved in immersive science learning. However, collaborative and discourse-based perspectives are also underrepresented in the study, as they tend to see the value of applying the analytic lenses of collective phenomena and shared constructions of meaning derived from talk and gesture in collaborative understanding that has taken place in common virtual spaces (Uz-Bilgin et al., 2020), which is a less-firmly entrenched part of the theoretical landscape that has been only lightly mentioned in this corpus.

The two thematic clusters emerging within the cluster, “immersive experience” and “disciplinary science pedagogy” highlight an interrelated tension in the field, that is often not fully developed. Most of the highest-cited research, such as that by Moro et al. (2017) and Lindgren et al. (2016), focuses on general topics of comparative effectiveness of immersive to traditional instruction, while a significant body of research addresses the topic of more specific questions regarding the design and implementation of immersive instruction within specific science content areas, chemistry, physics, or astronomy. Greater integration of these two research streams, making clear links from general theoretical statements about embodiment and presence to principles of instructional design in the target discipline, is a promising direction for theoretical synthesis.

VR dominates this corpus, with 84.5% of total articles, and AR and MR constitute only 15.5%, setting aside VR from its definition, which can be applied to AR and MR. While not unusual in the context of this study, this imbalance is no accident and has real consequences for one’s views on the overall state of the science education research base, as well as its implications for the field’s maturity. This VR dominant profile mirrors

the history of VR technology; the head mounted VR offers more accessible, consumer affordability and reliable research quality products compared to the marker-less AR tracking and environmentally-subbed MR, which finds a reliance on newer developments in computer vision and spatial mapping hardware (Cowling & Birt, 2018). Therefore, the theoretical and empirical representativeness seen within this study and mentioned here and there throughout, for example in connection with embodiment and presence theory, should be interpreted as a part of the mainstream of the field rather than the whole field, as VR approach to the field is the most known and prominent.

This asymmetry affects the interpretation of the results of both the keyword and co-citation analysis. The AR and MR application cluster identified in the thematic clusters and conceptual structure (RQ3) section is found to be real but a much smaller evidentiary base than found for the cluster of immersive experience, however, it is internally coherent and conclusions drawn are important and should be viewed as provisional when compared to the much more broadly replicated immersion findings. As MR and marker less AR tracking are the technological area with the greatest potential to advance the fields of spatial computing and metaverse science education, the lack of research evident in the literature discussed here leaves an opening for primary science studies focused directly on AR and MR science teaching.

The fact that 5 articles represent 44.0% of the total number of citations in the corpus is an interesting observation to consider. On the other hand, this concentration shows that theoretical and methodological impact of these pioneering works is well reflected in these studies, some of which added novel methods and conditions to subsequent studies, such as “embodied learning environments” using motion-capture system, and systematic comparisons, between VR and AR effectiveness, which have significantly influenced further study design practice across the field. However, this focus can also be a source of citation path dependency, in which a small number of influential studies likely serve as sources for literature reviews and theoretical construction of the problem by new entrants while methodologically well-conducted and less-cited studies which investigate similar or competing issues are not. The increase in publications in 2024 and 2025 suggests that the field is building a broader empirical base than its landmark founding studies alone provided, which is a sign of growing maturity of the discipline.

The results of this study expand and elaborate on those of other similar studies that rely on bibliometric analysis of studies on immersive and educational technology. In computer science education, there were themes that are dominant; the top two themes in this paper were: programming education and computational thinking (Agbo et al., 2021), which is in line with programming education and computational thinking identified by the computer science education cluster in the present keyword co-occurrence analysis but the present study spectrum of science education has resulted in a much larger and more varied literature that shows a far greater presence and variety of themes. Likewise, when looking at the evolution of artificial intelligence applications in higher education provider Zawacki-Richter (2019) finds that there is a similar trend of authorship clustering and rapid growth after 2015 across the broader educational technology field in higher education; thus, the geographic concentration, landmark publication concentration and accelerated recent production in the field of immersive science education research could be seen as representative of the broader sub-fields of educational technology in higher education and across other emerging disciplines.

CONCLUSION

The present study performed a comprehensive analysis of bibliometric information for 116 peer-reviewed journal articles concerning science education and the use of virtual and AR between 2006 and 2026 in the Scopus index. For the analysis four RQs were formulated: What were the structural characteristics of the publications? What were its effects on the impact of publication in the field? How was the theme of the publications distributed over the various themes fielded? What did the analysis of the publications reveal about the development of a field's themes over time?

The conclusions show that research in VR and AR in science education has progressed from an isolated and exploratory technological field to a field of inquiry with a mature substantive basis and high growth rates, on an international scale. The growth of publication over the last few years has been noteworthy, with a single article in 2006 producing numbers of citations that hit a peak of 4,742 annually by 2025 and equaled an h-index of 33, which is indicative of significant cumulative academic impact. The field reveals

internationalization, significant international diversification with 42 countries in six continents, the most productive national contexts being the United States, Australia, China and Greece. A few key articles have significantly influenced the landscape of citations to the literature: Moro et al. (2017) is the foundation for the embodied cognition tradition, and Lindgren et al. (2016) and Johnson-Glenberg et al. (2014) for the embodiment of presence theory traditions in the field.

The structure of the corpus is thematic, and the four thematic clusters are closely related themes of learning environments: namely the immersive experience cluster with focus on presence, engagement and collaborative virtual space in learning; the disciplinary science pedagogy cluster with science as the main focus and several aspects concerning the physics, chemistry, biology and astronomy education respective field applications; the augmented and MR applications cluster with focus on augmented and MR physical-digital learning environments; and the computer science education cluster, which is extensively associated with the immersive experience cluster as substantial science-technology development effort is needed in creating novel immersive science learning environments. The development history of the field suggests three stages, the first of which was from 2006 to 2013, in which a few major and technically important applications were explored through development work; the second, from 2014 to 2019, when the theoretical core of the field was consolidated through the publication of the major landmark studies; and the third, from 2020 to 2026, in which the field is expanding quickly and is diversifying in its methods and approaches to the development of new technological variants such as MR and computer science applications.

All of these results will compile a comprehensive – evidence-based – ‘map’ of the VR and AR research field in science education by providing a large picture overview of past research and its current focus while identifying the best theoretical resources for shaping the field. The map serves as a tool for science education researchers, science curriculum developers, teacher educators, and science institutional decision makers to strategically and informatively navigate the flood of literature in this expanding field.

Author contributions: All authors have sufficiently contributed to this study and agreed with the results and conclusions.

Funding: The authors received no financial support for the research and/or authorship of this article.

Ethics declaration: The authors stated that this study did not require ethics committee approval since it is based on articles already in the existing literature.

AI statement: The authors used AI-based tools just for language editing and grammar checking during the preparation of this manuscript. The whole scientific content, data interpretation and conclusions are the sole responsibility of the authors.

Declaration of interest: The authors declared no competing interest.

Data availability: Data generated or analyzed during this study are available from the authors on request.

REFERENCES

- Agbo, F. J., Sanusi, I. T., Oyelere, S. S., & Suhonen, J. (2021). Application of virtual reality in computer science education: A systemic review based on bibliometric and content analysis methods. *Education Sciences*, 11(3), Article 142. <https://doi.org/10.3390/educsci11030142>
- Aria, M., & Cuccurullo, C. (2017). *bibliometrix*: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, 11(4), 959-975. <https://doi.org/10.1016/j.joi.2017.08.007>
- Artun, H., Durukan, A., & Temur, A. (2020). Effects of virtual reality enriched science laboratory activities on pre-service science teachers' science process skills. *Education and Information Technologies*, 25(6), 5477-5498. <https://doi.org/10.1007/s10639-020-10220-5>
- Arvanitis, T. N., Petrou, A., Knight, J. F., Savas, S., Sotiriou, S., Gargalakos, M., & Gialouri, E. (2009). Human factors and qualitative pedagogical evaluation of a mobile augmented reality system for science education used by learners with physical disabilities. *Personal and Ubiquitous Computing*, 13(3), 243-250. <https://doi.org/10.1007/s00779-007-0187-7>
- Ateş, H., & Kölemen, C. Ş. (2025). Integrating theories for insight: An amalgamated model for gamified virtual reality adoption by science teachers. *Education and Information Technologies*, 30(2), 2123-2153. <https://doi.org/10.1007/s10639-024-12892-9>

- Çakıroğlu, Ü., Aydın, M., Özkan, A., Turan, Ş., & Cihan, A. (2021). Perceived learning in virtual reality and animation-based learning environments: A case of the understanding our body topic. *Education and Information Technologies*, 26(5), 5109-5126. <https://doi.org/10.1007/s10639-021-10522-2>
- Chang, C.-Y., Kuo, H.-C., & Du, Z. (2023). The role of digital literacy in augmented, virtual, and mixed reality in popular science education: A review study and an educational framework development. *Virtual Reality*, 27(3), 2461-2479. <https://doi.org/10.1007/s10055-023-00817-9>
- Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). Science mapping software tools: Review, analysis, and cooperative study among tools. *Journal of the American Society for Information Science and Technology*, 62(7), 1382-1402. <https://doi.org/10.1002/asi.21525>
- Cowling, M., & Birt, J. (2018). Pedagogy before technology: A design-based research approach to enhancing skills development in paramedic science using mixed reality. *Information*, 9(2), Article 29. <https://doi.org/10.3390/info9020029>
- Cullinane, A., McGregor, D., Frodsham, S., Hillier, J., & Guilfoyle, L. (2022). Transforming a doctoral summer school to an online experience: A response to the COVID-19 pandemic. *British Journal of Educational Technology*, 53(3), 558-576. <https://doi.org/10.1111/bjet.13195>
- Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, 133, 285-296. <https://doi.org/10.1016/j.jbusres.2021.04.070>
- Flegr, S., Kuhn, J., & Scheiter, K. (2023). When the whole is greater than the sum of its parts: Combining real and virtual experiments in science education. *Computers and Education*, 197, Article 104745. <https://doi.org/10.1016/j.compedu.2023.104745>
- Frøland, T. H., Heldal, I., Sjøholt, G., & Ersvær, E. (2020). Games on mobiles via web or virtual reality technologies: How to support learning for biomedical laboratory science education. *Information*, 11(4), Article 195. <https://doi.org/10.3390/info11040195>
- Garduño, H. A. S., Martínez, M. I. E., & Castro, M. P. (2021). Impact of virtual reality on student motivation in a high school science course. *Applied Sciences*, 11(20), Article 9516. <https://doi.org/10.3390/app11209516>
- Gercek, G., Saleem, N., & Stee, D. J. (2016). Implementing cloud based virtual computer network labs for online education: Experiences from a phased approach. *International Journal of Online Engineering*, 12(3), 70-76. <https://doi.org/10.3991/ijoe.v12i03.5564>
- Gonzalez, A. J., Hollister, J. R., DeMara, R. F., Leigh, J., Lanman, B., Lee, S.-Y., Parker, S., Walls, C., Parker, J., Wong, J., Barham, C., & Wilder, B. (2017). AI in informal science education: Bringing Turing back to life to perform the Turing test. *International Journal of Artificial Intelligence in Education*, 27(2), 353-384. <https://doi.org/10.1007/s40593-017-0144-1>
- Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. *PNAS*, 102(46), 16569-16572. <https://doi.org/10.1073/pnas.0507655102>
- Hite, R. L., Jones, M. G., Childers, G. M., Ennes, M., Chesnutt, K., Pereyra, M., & Cayton, E. (2019). Investigating potential relationships between adolescents' cognitive development and perceptions of presence in 3-D, haptic-enabled, virtual reality science instruction. *Journal of Science Education and Technology*, 28(3), 265-284. <https://doi.org/10.1007/s10956-018-9764-y>
- Huang, K.-T., Ball, C., Francis, J., Ratan, R., Boumis, J., & Fordham, J. (2019). Augmented versus virtual reality in education: An exploratory study examining science knowledge retention when using augmented reality/virtual reality mobile applications. *Cyberpsychology, Behavior, and Social Networking*, 22(2), 105-110. <https://doi.org/10.1089/cyber.2018.0150>
- Hu-Au, E., & Okita, S. (2021). Exploring differences in student learning and behavior between real-life and virtual reality chemistry laboratories. *Journal of Science Education and Technology*, 30(6), 862-876. <https://doi.org/10.1007/s10956-021-09925-0>
- Johnson-Glenberg, M. C., & Megowan-Romanowicz, C. (2017). Embodied science and mixed reality: How gesture and motion capture affect physics education. *Cognitive Research: Principles and Implications*, 2(1), Article 24. <https://doi.org/10.1186/s41235-017-0060-9>
- Johnson-Glenberg, M. C., Birchfield, D. A., Tolentino, L., & Koziupa, T. (2014). Collaborative embodied learning in mixed reality motion-capture environments: Two science studies. *Journal of Educational Psychology*, 106(1), 86-104. <https://doi.org/10.1037/a0034008>

- Kennedy-Clark, S. (2011). Pre-service teachers' perspectives on using scenario-based virtual worlds in science education. *Computers and Education*, 57(4), 2224-2235. <https://doi.org/10.1016/j.compedu.2011.05.015>
- Kersting, M., Bondell, J., Steier, R., & Myers, M. (2024). Virtual reality in astronomy education: Reflecting on design principles through a dialogue between researchers and practitioners. *International Journal of Science Education, Part B: Communication and Public Engagement*, 14(2), 157-176. <https://doi.org/10.1080/21548455.2023.2238871>
- Kersting, M., Steier, R., & Venville, G. (2021). Exploring participant engagement during an astrophysics virtual reality experience at a science festival. *International Journal of Science Education, Part B: Communication and Public Engagement*, 11(1), 17-34. <https://doi.org/10.1080/21548455.2020.1857458>
- Lamb, R., & Etopio, E. A. (2020). Virtual reality: A tool for preservice science teachers to put theory into practice. *Journal of Science Education and Technology*, 29(4), 573-585. <https://doi.org/10.1007/s10956-020-09837-5>
- Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers and Education*, 95, 174-187. <https://doi.org/10.1016/j.compedu.2016.01.001>
- Liu, R., Wang, L., Koszalka, T. A., & Wan, K. (2022). Effects of immersive virtual reality classrooms on students' academic achievement, motivation and cognitive load in science lessons. *Journal of Computer Assisted Learning*, 38(5), 1422-1433. <https://doi.org/10.1111/jcal.12688>
- Makransky, G., Petersen, G. B., & Klingenberg, S. (2020). Can an immersive virtual reality simulation increase students' interest and career aspirations in science? *British Journal of Educational Technology*, 51(6), 2079-2097. <https://doi.org/10.1111/bjet.12954>
- Marques, B., Santos, B. S., & Dias, P. (2024). Ten years of immersive education: Overview of a virtual and augmented reality course at postgraduate level. *Computers and Graphics*, 124, Article 104088. <https://doi.org/10.1016/j.cag.2024.104088>
- McElhaney, K. W., & Linn, M. C. (2011). Investigations of a complex, realistic task: Intentional, unsystematic, and exhaustive experimenters. *Journal of Research in Science Teaching*, 48(7), 745-770. <https://doi.org/10.1002/tea.20423>
- Meng, J. (2021). College physical education teaching aided by virtual reality technology. *Mobile Information Systems*. <https://doi.org/10.1155/2021/3052895>
- Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: A comparative analysis. *Scientometrics*, 106(1), 213-228. <https://doi.org/10.1007/s11192-015-1765-5>
- Moro, C., Štromberga, Z., Raikos, A., & Stirling, A. (2017). The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education*, 10(6), 549-559. <https://doi.org/10.1002/ase.1696>
- Mystakidis, S., & Christopoulos, A. (2022). Teacher perceptions on virtual reality escape rooms for STEM education. *Information*, 13(3), Article 136. <https://doi.org/10.3390/info13030136>
- Ogegbo, A. A., Penn, M., Ramnarain, U., Pila, O., Van Der Westhuizen, C., Mdalose, N., Moser, I., Hlosta, M., & Bergamin, P. (2024). Exploring pre-service teachers' intentions of adopting and using virtual reality classrooms in science education. *Education and Information Technologies*, 29(15), 20299-20316. <https://doi.org/10.1007/s10639-024-12664-5>
- Pande, P., Thit, A., Sørensen, A. E., Mojsoska, B., Moeller, M. E., & Jepsen, P. M. (2021). Long-term effectiveness of immersive VR simulations in undergraduate science learning: Lessons from a media-comparison study. *Research in Learning Technology*, 29. <https://doi.org/10.25304/rlt.v29.2482>
- Parmar, D., Lin, L., Dsouza, N., Jorg, S., Leonard, A. E., Daily, S. B., & Babu, S. V. (2023). How immersion and self-avatars in VR affect learning programming and computational thinking in middle school education. *IEEE Transactions on Visualization and Computer Graphics*, 29(8), 3698-3713. <https://doi.org/10.1109/TVCG.2022.3169426>
- Paxinou, E., Panagiotakopoulos, C. T., Karatrantou, A., Kalles, D., & Sgourou, A. (2020). Implementation and evaluation of a three-dimensional virtual reality biology lab versus conventional didactic practices in lab experimenting with the photonic microscope. *Biochemistry and Molecular Biology Education*, 48(1), 21-27. <https://doi.org/10.1002/bmb.21307>
- Petersen, G. B., Klingenberg, S., & Makransky, G. (2022). Pipetting in virtual reality can predict real-life pipetting performance. *Technology, Mind, and Behavior*, 3(3), 452-467. <https://doi.org/10.1037/tmb0000076>

- Poonja, H. A., Shirazi, M. A., Khan, M. J., & Javed, K. (2023). Engagement detection and enhancement for STEM education through computer vision, augmented reality, and haptics. *Image and Vision Computing*, 136, Article 104720. <https://doi.org/10.1016/j.imavis.2023.104720>
- Pritchard, A. (1969). Statistical bibliography or bibliometrics? *Journal of Documentation*, 25(4), 348-349. <https://doi.org/10.1108/eb026482>
- Reeves, S. M., Crippen, K. J., & McCray, E. D. (2021). The varied experience of undergraduate students learning chemistry in virtual reality laboratories. *Computers and Education*, 175, Article 104320. <https://doi.org/10.1016/j.compedu.2021.104320>
- Ruiz-Martínez, A., Pereníguez-García, F., Marín-López, R., Ruiz-Martínez, P. M., & Skarmeta-Gómez, A. F. (2013). Teaching advanced concepts in computer networks: VNUML-UM virtualization tool. *IEEE Transactions on Learning Technologies*, 6(1), 85-96. <https://doi.org/10.1109/TLT.2013.2>
- Scherer, R., & Tiemann, R. (2012). Factors of problem-solving competency in a virtual chemistry environment: The role of metacognitive knowledge about strategies. *Computers and Education*, 59(4), 1199-1214. <https://doi.org/10.1016/j.compedu.2012.05.020>
- Schloss, K. B., Schoenlein, M. A., Tredinnick, R., Smith, S., Miller, N., Racey, C., Castro, C., & Rokers, B. (2021). The UW virtual brain project: An immersive approach to teaching functional neuroanatomy. *Translational Issues in Psychological Science*, 7(3), 297-314. <https://doi.org/10.1037/tps0000281>
- Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. *Journal of the American Society for Information Science*, 24(4), 265-269. <https://doi.org/10.1002/asi.4630240406>
- Sung, Y.-T., Chang, K.-E., & Liu, T.-C. (2016). The effects of integrating mobile devices with teaching and learning on students' learning performance: A meta-analysis and research synthesis. *Computers and Education*, 94, 252-275. <https://doi.org/10.1016/j.compedu.2015.11.008>
- Takala, T. M., Malmi, L., Pugliese, R., & Takala, T. (2016). Empowering students to create better virtual reality applications: A longitudinal study of a VR capstone course. *Informatics in Education*, 15(2), 287-317. <https://doi.org/10.15388/infedu.2016.15>
- Ullah, M., Amin, S. U., Munsif, M., Safaev, U., Khan, H., Khan, S., & Ullah, H. (2022). Serious games in science education: A systematic literature review. *Virtual Reality and Intelligent Hardware*, 4(3), 189-209. <https://doi.org/10.1016/j.vrih.2022.02.001>
- UNESCO. (2023). *Global education monitoring report, 2023: Technology in education: A tool on whose terms?* UNESCO. <https://doi.org/10.54676/UZQV8501>
- Uz-Bilgin, C., Thompson, M., & Anteneh, M. (2020). Exploring how role and background influence through analysis of spatial dialogue in collaborative problem-solving games. *Journal of Science Education and Technology*, 29(6), 813-826. <https://doi.org/10.1007/s10956-020-09861-5>
- van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84(2), 523-538. <https://doi.org/10.1007/s11192-009-0146-3>
- Wee, C., Yap, K. M., & Lim, W. N. (2022). iProgVR: Design of a virtual reality environment to improve introductory programming learning. *IEEE Access*, 10, 100054-100078. <https://doi.org/10.1109/ACCESS.2022.3204392>
- Xie, C., & Lee, H.-S. (2012). A visual approach to nanotechnology education. *International Journal of Engineering Education*, 28(5), 1006-1018.
- Xie, T., Li, Y., & Tang, Y. (2023). Effects of using immersive virtual reality for science education on learning outcomes: A randomized controlled pilot study. *IEEE Transactions on Learning Technologies*, 16(6), 1045-1056. <https://doi.org/10.1109/TLT.2023.3263587>
- Xing, W., Huang, X., Li, C., & Xie, C. (2023). Teaching thermodynamics with augmented interaction and learning analytics. *Computers and Education*, 196, Article 104726. <https://doi.org/10.1016/j.compedu.2023.104726>
- Yang, Q.-F., Lin, H., Hwang, G.-J., Su, P.-Y., & Zhao, J.-H. (2024). An exploration-based SVVR approach to promote students' chemistry learning effectiveness. *Interactive Learning Environments*, 32(5), 2003-2027. <https://doi.org/10.1080/10494820.2022.2135106>
- Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education: Where are the educators? *International Journal of Educational Technology in Higher Education*, 16(1), Article 39. <https://doi.org/10.1186/s41239-019-0171-0>

- Zhao, Q., Xiong, C., Liu, K., Zhang, X., & Liu, Z. (2022). Cultivation design of applied undergraduates' engineering innovation ability based on virtualization technology. *Wireless Communications and Mobile Computing*. <https://doi.org/10.1155/2022/5500021>
- Zupic, I., & Čater, T. (2015). Bibliometric methods in management and organization. *Organizational Research Methods*, 18(3), 429-472. <https://doi.org/10.1177/1094428114562629>

