Educational Enhancement Through Augmented Reality Simulation: A Bibliometric Analysis

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***Abstract*—Augmented Reality (AR) has become a key technology in the education sector, offering interactive learning experiences that improve student engagement and understanding. Despite its increasing use, a thorough summary of AR research in educational environments is still required. This study applies bibliometric analysis to identify trends in this research field. Data from the Scopus database and VOSviewer software version 1.6.19 was used to analyze academic publications from 2018 to 2023. The original dataset of 4858 articles was narrowed down to 1109 articles concentrating on "augmented reality" AND "simulation" in student learning. Methods such as advanced data mining, co-citation analysis, and network visualization were utilized to outline the structure and trends in this research area. Key findings include a significant rise in research activity over the past decade, identification of the ten most prolific authors in AR simulation studies, and detailed visualizations of information distribution. Significant challenges include high costs and difficulties in technical integration. The study addresses these issues through interdisciplinary research that combines educational theory with AR technology. Results demonstrate growing interest in AR applications, particularly within STEM education, driven by technological advancements and increased funding. Despite these challenges, the potential of AR to enhance learning outcomes is clear. This research concludes that AR simulations can be a valuable educational tool, with further studies needed to explore the scalability of AR applications in various educational settings and to develop evidence-based guidelines for effective integration.**

Keyword—Augmented reality; simulation; learning; education

I. Introduction

In the ever-evolving landscape of education, the integration of emerging technologies holds immense promise for revolutionizing pedagogical approaches. Among these technologies, augmented reality (AR) has emerged as a powerful tool with the potential to enhance learning experiences across various domains. The use of augmented reality (AR) in education represents a significant transition from conventional teaching methods to a new era characterized by extremely interactive and captivating learning experiences [1]–[4]. AR presents a reality-like world with additional information which can be used to view objects in virtual or real-world environments.

The use of augmented reality (AR) allows students to interactively engage with three-dimensional models [5]-[7], historical re-enactments [8], [9], and sophisticated scientific phenomena [10] in real-time by seamlessly integrating digital overlays with the physical environment. This immersive method converts previously abstract or intricate information into concrete and easily understandable experiences, greatly improving understanding and involvement. The adaptability of AR extends across a wide range of disciplines, providing distinct advantages in each one. Medical students can utilize augmented reality (AR) simulations to engage in virtual surgical practice, acquiring significant practical experience without the inherent dangers associated with real-life surgeries [11]–[14]. Engineering students have the opportunity to analyze and engage with intricate machinery or infrastructures, which allows them to develop a more profound comprehension of design principles and spatial relationships [15]–[17]. Meanwhile, students studying history and archaeology can explore historical civilizations and locations in three dimensions, acquiring profound insights and a heightened sense of immersion that cannot be achieved through conventional textbook learning. These cutting-edge tools accommodate diverse learning styles, greatly enhancing motivation, involvement, and knowledge retention by transforming learning into a more dynamic and customized experience.

In addition, augmented reality simulations in educational settings go beyond simple visual engagement [18]–[20]. They provide a multi-sensory experience that replicates real-life situations, allowing learners to safely explore, experiment, and learn from their mistakes without facing real-world repercussions. AR simulations allow learners to refine their abilities in a controlled setting, bolstering their self-assurance and proficiency prior to employing them in real-life scenarios. Nevertheless, the incorporation of augmented reality (AR) into educational systems presents several obstacles, such as the substantial expenses linked to AR technology, the need for comprehensive infrastructure, and the demanding process for educators to effectively integrate AR into their teaching approaches. Despite these challenges, the future of augmented reality (AR) in education looks promising, driven by ongoing progress in technology that is enhancing the accessibility and user-friendliness of AR . With the decreasing cost of AR devices and the advancement of standardised AR educational content, the use of AR in educational settings is expected to grow, establishing its position as an essential element of modern educational tactics [21], [22]. Augmented reality has the exceptional ability to enhance learning by making it more immersive, personalised, and effective. It is poised to overcome current obstacles and significantly enhance the educational environment. This technology represents a new era of learning that connects theoretical knowledge with practical application.

By leveraging advanced bibliometric methods, this research provides new insights into how AR is shaping the future of education.

In contrast to earlier studies that mostly focused on individual case studies or specialized applications of AR, this research systematically examines a broad range of academic publications using advanced data mining, co-citation analysis, and network visualization techniques. The study identifies significant trends, key authors, and the most cited works, providing a holistic view of the current state of AR research in education. Additionally, it highlights the interdisciplinary nature of AR applications, demonstrating their impact across various fields such as STEM education, medical training, and engineering. This comprehensive approach allows for a deeper understanding of how AR simulations is being integrated into educational practices.

II. Literature Review

Research has demonstrated that AR simulations enhance student engagement, motivation, and knowledge retention [23], [24] where students using AR are more interested in their lessons and more likely to stay focused. The interactive nature of AR makes learning activities more enjoyable, which increases motivation. By superimposing digital information onto the physical world, AR creates an immersive learning environment [25], [26]. This allows students to interact with virtual objects and scenarios in a more intuitive and captivating way. AR simulations have proven effective across diverse fields such as science, engineering, health, and social sciences. For instance, in medical education, AR is used to teach students about anatomy and physiology, enabling them to engage with virtual organs and systems in an authentic and immersive manner [27], [28]. This can help in visualizing complex physiological processes, such as blood circulation and neural pathways, making them easier to understand. In engineering education, AR is employed to teach principles such as mechanical systems and circuit design [29]–[31], allowing students to interact with virtual models and observe their real-time behavior [32], [33].

Despite the significant advantages of AR simulations, various challenges and constraints need to be addressed. A key challenge is the creation of high-quality AR content that is both engaging and educational. This requires proficiency in AR design and development, as well as a deep understanding of the subject matter [34]. Another challenge is the cost and accessibility of AR technology. While the cost of AR technology has decreased in recent years, developing high-quality AR content still demands a substantial financial investment. Researchers have explored the use of open-source AR development tools and platforms, such as ARKit and ARCore, to help reduce these costs. To optimize the educational benefits of AR simulations, researchers have developed various pedagogical approaches and design principles. For example, the "AR-based learning cycle" suggests that AR simulations should be designed to promote active learning, problem-solving, and critical thinking. Additionally, researchers have identified specific design principles to ensure the educational effectiveness of AR simulations, including realism, interactivity, personalization, and feedback.

By adhering to these principles, educators can create engaging and interactive AR simulations that foster active learning and critical thinking. As AR technology continues to advance, AR simulations are likely to become increasingly important tools for educators across various fields. By utilizing AR simulations, educators can create innovative and engaging learning experiences that help students develop a deeper understanding of the subject matter, equipping them with the skills and knowledge needed to succeed in their future careers. This approach aligns with [35], who advocate for integrating AR in teacher training, particularly for simulation and modeling in science education, underscoring AR's capacity to elevate digital competencies among future educators. The study in [36] highlight the perceptual challenges posed by blending virtual and physical content in AR environments, emphasizing the need to address these incongruities for a seamless learning experience.

Innovative approaches to AR simulations in medical and robotics education are presented by [37] and [38]. [37] describe an AR-based technique for visualizing brain deformations during surgical procedures, while [38] explore AR's role in mobile robotics, emphasizing its educational value in understanding autonomous systems. The research in [39] expands the application of AR beyond medical and scientific realms into interior design, illustrating AR's versatility in enhancing visualization and communication between designers and clients. The reviewed studies collectively underscore AR's potential to revolutionize educational and training paradigms across disciplines.

III. Research Question

This paper attempts to respond to six (6) primary research questions.

RQ 1: What are the research trends in augmented reality simulation according to the year of publication?

RQ 2: Who are the top ten most active authors in ar simulation publications?

RQ 3: What are the most cited articles by subject of research?

RQ 4: What is the map of Co-Authorship?

RQ 5: What are the popular keywords related to the study?

RQ 6: What are co-authorship countries' collaboration on the use of AR simulation in education?

IV. Methodology

Bibliometrics involves the collection, organisation, and analysis of bibliographic data from scientific publications [40]–[42]. In addition to basic descriptive statistics like publishing journals, publication year, and major author categorization [43], the analysis also includes advanced approaches such as document co-citation analysis. To do a successful literature review, one must engage in an iterative process that includes identifying relevant keywords, conducting a literature search, and thoroughly analysing the gathered information to create a full bibliography and obtain reliable outcomes [44]. The study aimed to concentrate on top-tier papers since they provide significant insights into the theoretical views influencing the development of the research field. The study utilised the SCOPUS database for data gathering to assure data dependability [45]–[47]. Only articles from rigorously peer-reviewed academic journals were evaluated to ensure high-quality publications. Books and lecture notes were deliberately excluded [48]. Elsevier's Scopus, renowned for its comprehensive coverage, gathered publications from 2018 to December 2023 for analysis.

A. Data Search Strategy

Study employed a screening sequence to determine the search terms for article retrieval. As shown in Table I, this study was initiated by querying Scopus database with online Augmented Reality Simulation for Educational Enhancement (“augmented reality”) AND (simulation) thereby assembling 4858 articles. Afterwards, the query string was revised so that the search terms “augmented reality” AND “simulation” should be focussed on students as learners. Refinement included 1109 articles which was used for bibliometric analysis as shown in Table II. As of February 2024, all articles from Scopus database relating augmented reality and simulation in learning, were incorporated in the study.

TABLE I. THE SEARCH STRING

Database	Search String
Scopus	TITLE-ABS-KEY ("Augmented Reality" AND simulat* AND (education OR learn* OR teach*)) AND (LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023))

TABLE II. THE SELECTION CRITERION IN SEARCHING

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2018 – 2023	< 2018
Document Type	Article	Non-Article
Literature type	Journal	Book, Review, Proceeding

B. Data Analysis

The data sets containing information about the study's publication year, title, author, journal, citations, and keywords in plain text format were acquired from the Scopus database, covering the period from 2018 to December 2023. These data sets were analyzed using the VOSviewer software version 1.6.19. This software was utilized for analysis and map formation, employing the VOS clustering and mapping techniques. VOSviewer is an alternative to the Multidimensional Scaling (MDS) approach, and it is similar to MDS in its aim of placing items in a low-dimensional space in such a way that the relatedness and similarity between any two items are accurately reflected by the distance between them. Unlike MDS, which focuses on computing similarity measures like Jaccard indexes and cosine, VOSviewer implements a more suitable technique for normalizing co-occurrence frequencies, such as the association strength (ASij), calculated as:

$$AS_{ij} = \frac{C_{ij}}{w_i \times w_j}$$

Where;

- AS_{ij} represents the association strength between items i and j
- C_{ij} is the number of co-occurrences of items i and j
- W_i is the weight or total number of occurrences of item i
- W_j is the weight or total number of occurrences of item j

This association strength is proportional to the ratio between the observed number of co-occurrences of i and j and the expected number of co-occurrences of i and j, assuming that their co-occurrences are statistically independent. By using this index, VOSviewer places items on a map after reducing the weighted sum of the squared distances between all item pairs. According to Appio et al. (2016), the LinLog/modularity normalization was implemented. Furthermore, by applying visualization techniques through VOSviewer to the data set, patterns based on mathematical relationships were uncovered, and analyses such as keyword co-occurrence, citation analysis, and co-citation analysis were performed. Keyword co-occurrence analysis helps explore the development of a research area during a specific period and is successful in identifying popular topics in different fields. Citation analysis is useful in identifying key research issues, trends, and techniques, as well as exploring the historical relevance of a discipline's main area of focus. Document co-citation analysis is one of the frequently applied bibliometric methods and its result is a map dependent on network theory to identify the relevant structure of the data.

V. RESULT AND FINDING

The study of the extracted research on scholarly classification covers various aspects, including the types of documents and sources, annual growth trends, languages of the documents, subject areas, keyword analysis, country-level productivity, authorship patterns, and citation analysis. The findings of this paper are predominantly presented through frequency distributions, percentages, graphical representations, and visualization maps.

A. RQ 1: What are the Research Trends in Augmented Reality Simulation According to the Year of Publication?

Fig. 1 below presents the research trends in augmented reality simulations, highlighting the number of publications per year. The trend analysis offers insights into the growing attention augmented reality simulations have received in the academic community, reflecting the advancements and increasing focus on this technology in educational research.

The line graph shows a clear and consistent upward trend in the number of publications related to Augmented Reality (AR) for educational enhancement, with a slight acceleration in the last two years (2022 and 2023). Here are some possible factors that may have influenced this trend. As AR technology has become more affordable, accessible, and user-friendly, it has attracted increasing interest from researchers and educators who are exploring its potential applications in education. There is a growing body of research that suggests that AR can be an effective tool for enhancing learning and engagement in a variety of educational settings. This growing awareness is likely driving more researchers to explore the potential of AR in education. Governments and private organizations are increasingly investing in AR research, including research on the use of AR in education. This increased funding is likely to provide more resources for researchers to study and develop AR-based educational tools.

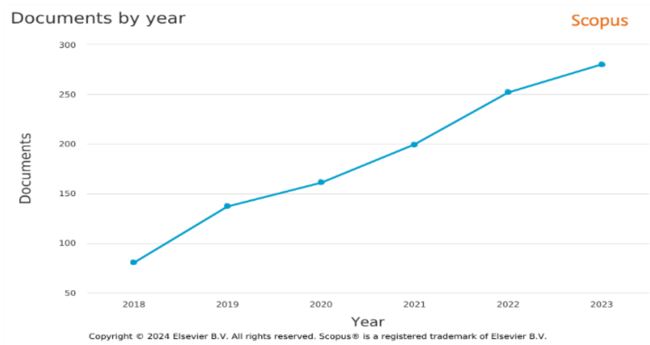

Fig. 1. Plotting of document publication by years.

There is a growing emphasis on using technology to personalize learning and create more engaging learning experiences. AR aligns well with these priorities, as it can provide students with individualized and interactive learning experiences. The increasing number of publications on AR for educational enhancement suggests that this is a growing field with a lot of potential. Some potential implications of this trend include the development of new and more effective AR-based educational tools. As more researchers study the use of AR in education, we are likely to see the development of more effective and engaging AR-based learning tools. The wider adoption of AR in classrooms. As AR-based educational tools become more available and affordable, we are likely to see them being adopted in more classrooms around the world. Changes in teaching practices. The use of AR in education may lead to changes in teaching practices, as teachers adapt their methods to take advantage of the new affordances offered by AR.

RQ 1: What are the Research Trends in Augmented Reality Simulation According to the Year of Publication?

RQ 2: Who are the Top Ten Most Active Authors in AR Simulation Publications?

The top ten most prolific authors in the field of Augmented Reality (AR) for educational enhancement are listed in Table III, with their respective number of publications ranging from four to seven. This ranking highlights the significant contributions made by these researchers, who have consistently produced valuable scholarly works that advance our understanding and application of AR technologies in educational contexts.

The list of top publication authors highlights key contributors to the field of augmented reality (AR) simulations in education. Ferrari, V., leading with seven publications, is central in pioneering research and developing methodologies within this domain. Ferrari's work likely spans technical innovations in AR software and hardware, as well as practical applications for immersive learning environments. The consistent presence of Ferrari, V. underscores a significant impact on both theoretical and practical aspects of AR in education. Condino, S., with six publications, is another prominent figure, focusing on integrating AR technologies into specific educational settings like medical or engineering training. Condino's contributions likely include evaluating AR simulations' effectiveness in enhancing learning outcomes, student engagement, and retention. The efforts of other authors such as Cutolo, F., Hanalioglu, S., and Tai, Y., contribute to a dynamic and interdisciplinary field. These scholars' diverse expertise covers the design, implementation, and assessment of AR simulations in education. Their research addresses challenges and opportunities in user interface design, content development, and curriculum integration. Collectively, these authors are advancing how educational content is delivered, paving the way for future innovations in the educational landscape. In conclusion, the leading authors in "Augmented Reality Simulation for Educational Enhancement," particularly Ferrari, V. and Condino, S., are driving a transformative movement in education. Their diverse research topics and innovative approaches are crucial in leveraging AR's potential to revolutionize learning. As the field evolves, their contributions will serve as essential references, fostering further integration of AR in education to create more engaging, effective, and immersive learning environments.

B. RQ 3: What are the Most Cited Articles by Subject of Research?RQ 1: What are the Research Trends in Augmented Reality Simulation According to the Year of Publication?

Table IV showcasing the 10 most cited articles in the field of augmented reality (AR) for educational enhancement, as analyzed through Scopus, provides a comprehensive overview of the current state and impactful trends within this interdisciplinary domain.

TABLE III. THE TOP TEN MOST ACTIVE AUTHORS

Author Name	**Number of Publication**	**Percentage (%)**
Ferrari, V.	7	1.74
Condino, S.	6	1.49
Cutolo, F.	5	1.24
Hanalioglu, S.	5	1.24
Tai, Y.	5	1.24
Aebersold, M.	4	1.00
Chinesta, F.	4	1.00
Cueto, E.	4	1.00
Frizziero, L.	4	1.00
Gungor, A.	4	1.00

TABLE IV. THE MOST CITED ARTICLE

Authors	Title	Year	Source title	Cited by
Yu et al., (2019)	Skin-integrated wireless haptic interfaces for virtual and augmented reality	2019	Nature	557
Ibáñez & Delgado-Kloos, (2018)	Augmented reality for STEM learning: A systematic review	2018	Computers and Education	493
Shi et al., (2021)	Towards real-time photorealistic 3D holography with deep neural networks	2021	Nature	255
Ge et al., (2019)	A bimodal soft electronic skin for tactile and touchless interaction in real time	2019	Nature Communications	181
de Paula Ferreira et al. ,(2020)	Simulation in industry 4.0: A state-of-the-art review	2020	Computers and Industrial Engineering	151
Pulijala Y.; Ma M.; Pears M.; Peebles D.; Ayoub A.	Effectiveness of Immersive Virtual Reality in Surgical Training- A Randomized Control Trial	2018	Journal of Oral and Maxillofacial Surgery	137
Ren J.; He Y.; Huang G.; Yu G.; Cai Y.; Zhang Z.	An Edge-Computing Based Architecture for Mobile Augmented Reality	2019	IEEE Network	103
Condino S.; Turini G.; Parchi P.D.; Viglialoro R.M.; Piolanti N.; Gesi M.; Ferrari M.; Ferrari V.	How to build a patient-specific hybrid simulator for orthopaedic open surgery: Benefits and limits of mixed-reality using the Microsoft hololens	2018	Journal of Healthcare Engineering	98
Birt J.; Stromberga Z.; Cowling M.; Moro C.	Mobile mixed reality for experiential learning and simulation in medical and health sciences education	2018	Information (Switzerland)	96
Al Janabi H.F.; Aydin A.; Palaneer S.; Macchione N.; Al-Jabir A.; Khan M.S.; Dasgupta P.; Ahmed K.	Effectiveness of the HoloLens mixed-reality headset in minimally invasive surgery: a simulation-based feasibility study	2020	Surgical Endoscopy	92

The leading article by Yu X. et al. (2019) in Nature, with 557 citations, explores "Skin-integrated wireless haptic interfaces for virtual [49] and augmented reality", highlighting the cutting-edge integration of sensory feedback mechanisms into AR systems. This work underscores the evolution of AR technologies towards more immersive and tactilely engaging experiences, which can significantly enhance the realism and effectiveness of educational simulations. Following closely is the systematic review by Ibáñez M.-B and Delgado-Kloos C. (2018) in Computers and Education, cited 493 times, which delves into "Augmented reality for STEM learning". This article synthesizes research findings on the application of AR in Science, Technology, Engineering, and Mathematics education, providing a critical assessment of AR's educational benefits, challenges, and future directions. The high citation count reflects the growing interest and recognition of AR's potential to transform traditional learning paradigms by making complex concepts more accessible and engaging through visualization and interaction. Shi L. et al.'s (2021) publication in Nature, "Towards real-time photorealistic 3D holography with deep neural networks", with 255 citations, represents a significant technological advancement in rendering lifelike 3D holograms. This leap forward in holography, powered by deep learning, has profound implications for educational content delivery, enabling students to explore and interact with high-fidelity simulations of physical phenomena, historical reconstructions, and intricate biological structures in real-time, thereby deepening understanding and retention. Moreover, the diverse range of topics covered by the other highly cited articles, from Ge J. et al.'s (2019) exploration of "A bimodal soft electronic skin" in Nature Communications to the practical applications of AR in surgical training and Industry 4.0 simulations, illustrates the broad applicability and transformative potential of AR in various educational contexts. These studies collectively highlight the multifaceted benefits of AR in enhancing educational outcomes, including increased engagement, improved understanding of complex subjects, and the provision of hands-on experiential learning opportunities without the constraints of physical materials or environments.

C. *RQ 4: What are the Map of Co-Authorship about AR Simulation?*

The data shown in Fig. 2, created using the Vosviewer analyzer, illustrates the bibliometric connections of co-authorship in the field of Augmented Reality Simulation for Educational Enhancement. The analysis seems to focus on the co-authorship network, revealing how many documents each set of authors has worked on together, the number of citations their work has received, and the total link strength between them.

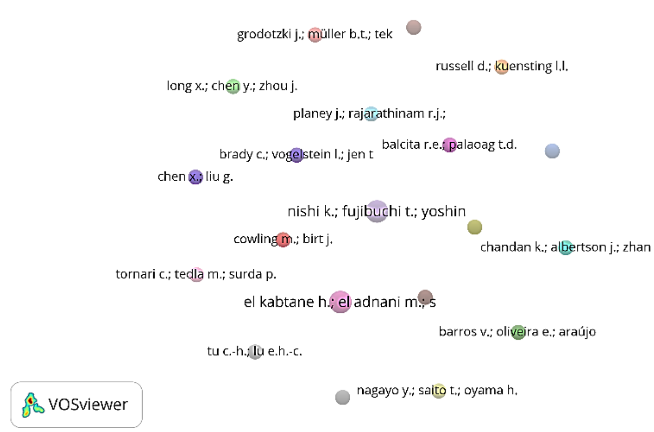

Fig. 2. Network visualization map of co-authorship.

Starting with the authors Balcita R.E. and Palaoag T.D., they have co-authored two documents that have accumulated a total of 8 citations. However, the total link strength is zero, which could imply that their collaborative work, while cited, is not central to the network of co-authorships being analyzed. Similarly, the teams of Barros V., Oliveira E., and Araújo L., as well as Brady C., Vogelstein L., Jen T., and Dim E., each have produced 2 documents, but these have not yet been cited. Cao

Y. also has two documents to their name with no citations and no link strength, indicating that their work is yet to gain traction in the field. Chandan K., Albertson J., and Zhang S., with the same number of documents, have received a single citation, again with no link strength. Chen X. and Liu G. stand out with their work being cited 78 times, suggesting that their research is highly recognized in the academic community, even though their link strength remains at zero. Cowling M. and Birt J. have also made a notable impact, with their 2 documents receiving 29 citations. The group of Diniz F., Duarte N., Amaral A., and Pereira C. has garnered 4 citations from their pair of documents. El Kabtane H., El Adnani M., Sadgal M., and Mourdi Y. have a slightly larger body of work, with 3 documents receiving 25 citations, indicating a significant contribution to the field. Other author groups, such as Grodotzki J., Müller B.T., and Tekkaya A.E., as well as Majgaard G. and Weitze C., have works that have been acknowledged 5 times in academic citations. The pairings of Nagayo Y., Saito T., Oyama H., and Solmaz S., Van Gerven T., have each received 19 citations for their 2 documents, suggesting their research is of considerable interest.

Nishi K., Fujibuchi T., and Yoshinaga T. have 3 documents with 20 citations, which indicates a productive collaboration. Planey J., Rajarathinam R.J., Mercier E., Lindgren R., and Zhou R., despite having authored 2 documents together, have not yet seen citations, indicating either recent publication or a delay in recognition. Russell D. and Kuensting L.L. have a modest citation count of 1 for their 2 documents, showing initial engagement with their work. Tornari C., Tedla M., and Surda P., as well as Tu C.-H and Lu E.H.-C., and the group of Wang L., Du W., Chu S., Shi M., and Li J., have authored 2 documents each but have not yet received citations, which suggests potential for future academic impact. Overall, the analysis reveals a diverse range of collaborations with varying degrees of recognition and impact within the scholarly community. The absence of total link strength across the board indicates that these connections might not be central within the larger network of co-authorships in this research domain, or it may reflect a limitation in the dataset or methodology used for this specific analysis.

D. *RQ 5: What are the Popular Keywords Related to the Study?*

The data shown in Fig. 3, created using the Vosviewer analyzer, illustrates the bibliometric connections of co-authorship in the field of Augmented Reality Simulation for Educational Enhancement. The analysis seems to focus on the co-authorship network, revealing how many documents each set of authors has worked on together, the number of citations their work has received, and the total link strength between them.

The bibliometric analysis illuminates the extensive influence of augmented reality (AR) simulations on educational enhancement. The preeminent keyword "augmented reality" exhibits 671 occurrences and a substantial total link strength of 1238, signifying its centrality. Closely related terms like "mixed reality" (98 occurrences, 265 link strength), "extended reality" (41 occurrences, 129 link strength), and "augmented reality (ar)" (41 occurrences, 68 link strength) solidify the interconnectivity within this domain. The prominence of keywords such as "education" (108 occurrences, 274 link strength), "medical education" (48 occurrences, 139 link strength), "educational innovation" (11 occurrences, 32 link strength), and "educational technology" (9 occurrences, 22 link strength) highlights the profound impact of AR simulations on educational applications across diverse disciplines. Notably, the data underscores the significant emphasis on simulation and training applications, particularly in medical and surgical domains, with keywords like "simulation" (145 occurrences, 357 link strength), "training" (55 occurrences, 144 link strength), "simulation training" (19 occurrences, 35 link strength), and "surgical training" (22 occurrences, 54 link strength) exhibiting high frequencies and link strengths.

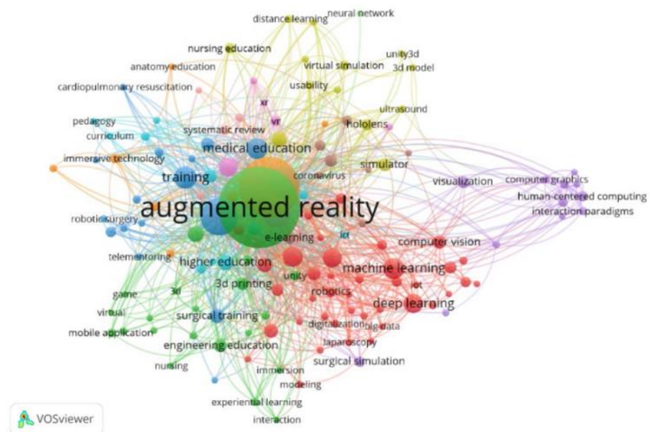

Fig. 3. Network visualization map of keywords' co-occurrence.

The analysis reveals strong connections between AR simulations and emerging technologies, including "artificial intelligence" (46 occurrences, 130 link strength), "machine learning" (47 occurrences, 109 link strength), "deep learning" (40 occurrences, 67 link strength), and "industry 4.0" (21 occurrences, 27 link strength), suggesting the potential for integrating cutting-edge technologies to enhance AR simulations' capabilities in educational contexts. Furthermore, the data highlights specific application areas exploring AR simulations for educational purposes, such as "neurosurgery" (20 occurrences, 54 link strength), "nursing education" (12 occurrences, 37 link strength), "dental education" (13 occurrences, 24 link strength), and "laparoscopy" (7 occurrences, 19 link strength). In summary, this bibliometric analysis accentuates the pivotal role of AR simulations in driving educational innovation and transformation across various domains, including medical and engineering such as electronics learning. The interdisciplinary nature of this research area, spanning educational applications and emerging technologies, underscores its vast potential for further exploration and development.

E. *RQ 6: What are Co-Authorship Countries' Collaboration on the use of AR Simulation in Education?*

Fig. 4 illustrates the co-authorship countries' collaboration on the use of AR simulation in education. Co-authorship analysis is the relatedness of items is determined based on the number of co-authored documents. The network visualization depicts international research collaborations centered on utilizing augmented reality (AR) simulations for educational purposes. Multiple nations are interconnected, with line thickness indicating collaboration intensity. The United States emerged as a prominent hub, exhibiting numerous connections with other countries. This observation aligns with the provided data, where the United States holds the highest document count (346) and total link strength (143). The network visualization depicts international research collaborations centered on utilizing augmented reality (AR) simulations for educational purposes. Multiple nations are interconnected, with line thickness indicating collaboration intensity. The United States emerged as a prominent hub, exhibiting numerous connections with other countries.

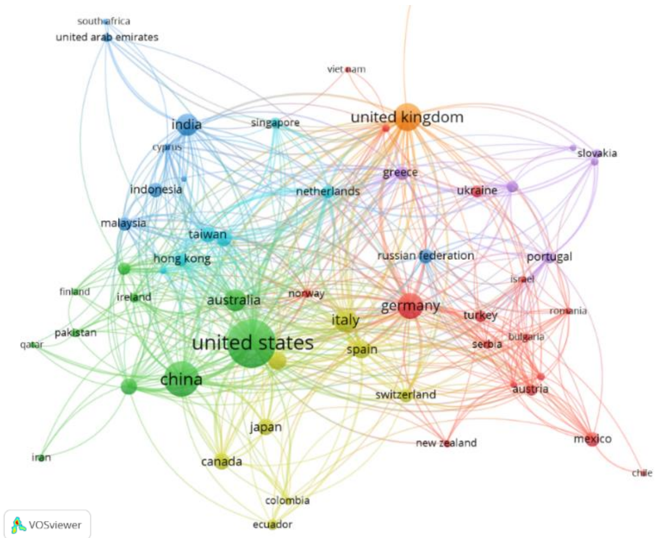

Fig. 4. The co-authorship countries' collaboration on the use of AR simulation in education.

This observation aligns with the provided data, where the United States holds the highest document count (346) and total link strength (143). The United Kingdom also stands out as a major collaborator, ranking second in document output (115) and total link strength (134). Several European nations like Germany, Italy, Spain, and the Netherlands exhibit strong collaboration ties within the region and globally. Germany and China follow as significant contributors, with 99 and 180 documents, respectively, alongside substantial link strengths of 119 and 101. Asian countries like China, India, South Korea, Taiwan, and Hong Kong demonstrate robust regional cooperation in this research domain. Certain nations with relatively fewer documents still maintain substantial collaboration links, exemplified by Cyprus (8 documents, 43 link strength) and Morocco (7 documents, 22 link strength). The analysis unveils a globally distributed research network focused on AR simulation for education, facilitated by regional clusters and international partnerships spanning multiple continents. The United States, United Kingdom, China, and Germany emerge as prominent hubs driving collaborative efforts in this field.

VI. Discussion and Conclusion

A. Main Findings of the Study

The bibliometric analysis conducted reveals significant trends and developments in the use of Augmented Reality (AR) simulations in education between 2018 and 2023. During this period, there was a noticeable increase in research activity, indicating a growing interest in the transformative potential of AR technology in educational practices. The analysis highlighted frequent keywords such as "simulation," "training," and "education," reflecting AR's broad applicability across various fields. Additionally, leading authors and highly cited articles were identified, showcasing key contributors who have significantly influenced the field.

B. Comparison with Other Studies

Unlike previous studies that focused primarily on specific applications or case studies of AR, this research provides a comprehensive overview of academic publications through advanced data mining, co-citation analysis, and network visualization techniques. This study extends those findings by illustrating the interdisciplinary nature of AR applications and their impacts across various fields like STEM [50], medical training, and engineering. The analysis also emphasizes the importance of international collaboration, with major contributions from countries like the United States, the United Kingdom, and China.

C. Implication and Explanation of Findings

The findings suggest that AR technology is particularly beneficial in fields requiring practical, hands-on experience. By allowing interaction with complex systems and scenarios in a controlled environment, AR helps transform theoretical concepts into tangible learning experiences. This capability makes AR an essential tool for modern education. Advancements in AR hardware and software, along with increased funding, have driven the rising interest in this technology. The study also highlights the growing trend of interdisciplinary research, blending educational theory with AR technology to enhance learning outcomes.

D. Strengths and Limitations

The strength of this study lies in its comprehensive approach, utilizing advanced bibliometric methods to provide a holistic view of AR research in education. However, there are limitations, including the focus on articles indexed in the Scopus database, which might exclude relevant studies from other databases. Additionally, the analysis is limited to publications up to 2023, potentially missing emerging trends beyond this period.

E. Conclusion

AR simulations represent a significant advancement in educational technology, offering unique opportunities to improve learning outcomes through immersive and interactive experiences. Despite challenges such as high costs, the need for extensive infrastructure, and the requirement for educators to adapt to new teaching methods, the benefits of AR in education are evident. AR's ability to transform abstract concepts into tangible experiences and provide safe, practical training scenarios is unparalleled.

VII. Suggestion for Future Research

Interest in integrating learning strategies with Augmented Reality (AR) technology in education is rapidly increasing. Consequently, it is crucial for researchers to meticulously plan and design well-structured teaching and learning components before implementing the technology in educational settings.

These components should address several key elements: (1) a comprehensive understanding of students' needs, (2) clearly defined learning objectives, (3) appropriate forms of support such as necessary equipment and resources, and (4) the identification and application of learning strategies that best match the specific needs of the students. Moreover, it is important to explore the potential of AR technology to enhance the learning process. This exploration involves determining whether AR can significantly improve students' skills and deepen their understanding of complex and abstract concepts. Additionally, more studies are needed to examine the long-term effects of AR on learning outcomes and to develop standardized AR educational content that can be widely adopted across various educational institutions. Such an investigation is essential to provide a more comprehensive and engaging learning experience that fulfills the diverse educational requirements of students.

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