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Research article

# Exploring the Potentials of Augmented Reality in Medical Education: A Bibliometric Analysis and Scientific Visualization

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## ABSTRACT

Alongside the COVID-19 pandemic, digitalization has significantly impacted medical education. The pandemic has necessitated several adaptations, including transitioning from a traditional learning model to a digital-based one. One form of this is augmented reality (AR). The future adoption of AR in medical education is bright and considerable. Therefore, evaluating AR in medical education is essential. One such method is bibliometric analysis. Using comprehensive bibliometric analysis, we aimed to collect data on the tendencies of this topic. The research examined terms, countries/territories, publication numbers, institutions, authors, and published journals. The Scopus database was used to compile the material. VOSviewer analyzed the complete bibliometric information. The analysis was based on data from 379 Scopus papers that met our criteria. The statistics demonstrated that the most significant expansion occurred in 2021, with the USA being the most productive country. The Journal of Studies in Health Technology and Informatics is the leading publication, and the Aristotle University of Thessaloniki has published the most papers. "The effectiveness of virtual and augmented reality in health sciences and medical anatomy" is the most cited paper. Bamidis, P. D., and Moro, C., made the most significant research contributions. In this field, further study is required, particularly in emergency medicine and clinical skills training for medical students. In conclusion, implementing augmented reality in medical education has tremendous potential.

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## 1. Introduction

In the present era, scientific technology and digitalization have significantly impacted work productivity and efficiency across various disciplines, including medical science. In the development of medical science, technology has played a crucial role in improving the understanding and management of human body systems [1], [2]. Medical science constantly changes content and structure based on advances and understanding of diverse healthcare needs [3].

Based on the current situation, the training and preparation of medical students to become competent doctors have become increasingly vital. Moreover, the changing crisis after the COVID-19 pandemic has affected the global health landscape. In light of this, digital learning methods have gained considerable relevance as they support efforts to mitigate the spread of COVID-19 [4]–[6]. In addition,

digital platforms in medical education offer greater efficiency, enabling seamless communication between students and teachers regardless of location or time constraints [7], [8].

Digital learning in medical education aims to enhance students' independent learning and literacy, improve teamwork, problem-solving, critical thinking skills, and bridge the gap between theory and practice [9]. It can support the undergraduate students' educational process and train residents pursuing specialization education. One of the applications of digital learning forms in medical education is augmented reality [2].

Augmented reality (AR) is a technology that augments the user's perception of the natural world. AR enables users to see and interact with digital content integrated into the real world in real-time [10], [11]. AR can help users understand an object's structure through visualizations, making it an effective medium for achieving learning goals [12]. Based on previous studies, the future application of AR in medical education is considered bright and relatively large [2], [13]. Therefore, evaluating and examining current AR research in medical education is crucial.

Research on AR in medical education with bibliometrics is important because it can provide insights into the current state of research, identify knowledge gaps, and inform future research directions. AR holds the potential to transform medical education by providing a more immersive and interactive learning environment. Through AR, students can visualize intricate anatomical structures and physiological processes in three dimensions, thereby enhancing their comprehension of the subject matter. Furthermore, AR can provide a more engaging and stimulating learning experience, which can lead to better knowledge retention and improved student performance.

Bibliometric analysis can be used to assess the impact and productivity of research in the field of AR in medical education. It can help identify the most influential authors, institutions, and journals, as well as the most cited papers and research themes. This information is invaluable in understanding the current state of research, recognizing research gaps and prospects, and shaping future research directions. Moreover, bibliometric analysis enables the tracking of research trends over time, which can help researchers and educators stay up-to-date with the latest developments in the field.

In the literature review conducted, a bibliometric article discussing the application of mixed reality (MR) in the medical field was identified [14]. However, this article does not specifically address the correlation between the application of augmented reality in medical education and is limited to the years 1995–2015. Further in-depth analysis, such as bibliometric analysis, is needed to understand the development of research concerning the utilization of augmented reality within the realm of medical education. Bibliometric analysis is considered capable of providing an overview and mapping related to the future sustainability of a research topic [15], [16]. Therefore, by employing bibliometric analysis, we intend to undertake additional investigations regarding the applicability of augmented reality in medical education. We will conduct further research on the development of AR in medical education through bibliometric analysis using the VOSviewer software and Bibliometrix and expand the year range to 2022.

We attempted to gather information on the tendencies of this scientific field through a comprehensive bibliometric study. The study examined terms, co-occurrence, countries/territories, publication numbers, institutions, authors, and published journals. A bibliometric and visual study was conducted to develop a comprehensive knowledge map of AR in medical education. Additionally, bibliometric analysis will be utilized to determine future research directions.

## 2. Materials and methods

### 2.1. Data source and search strategy

Scopus, one of the largest databases of curated abstracts and citations [16], [17], was selected to collect the data on August 15, 2022. Scopus is widely used as a source of bibliometric data [17]. A topic-specific search in the Scopus database was conducted using the following query (title, abstract, or keywords): ("augmented reality" AND "medical education" OR "medical learning" OR "medical teaching") AND (LIMIT-TO (LANGUAGE, "English")). This search yielded 379 papers published between 2001 and 2022, which were included in the final data analysis. The aim of this research is to visualize the overall development of the themes of augmented reality and medical education, making the process of finding publications open-ended. The first paper on augmented reality and medical education was found in

early 2001, according to our findings. This research involved neither human participants nor animal models, and therefore no ethical clearance was necessary.

## 2.2. Data analysis

The total publication records were exported to VOSviewer and Bibliometrix for further bibliometric analysis and visualization. VOSviewer was employed to visually analyze co-authorship and co-occurrence [18]. In this analysis, circles represent countries and author keywords. The distance between two circles indicates the strength of the relationship between terms, with greater distances indicating weaker relationships. Various colors are used to represent different term clusters. The size of the circles correlates positively with the frequency of occurrence of the times, and the line thickness represents the strength of the relationship between terms. An increase in the circle's diameter indicates a higher term frequency, while an increase in line thickness indicates a stronger relationship [18]. Meanwhile, Bibliometrix is an open-source application for conducting exhaustive science mapping analyses. It facilitates a suggested workflow for bibliometric analysis. [19].

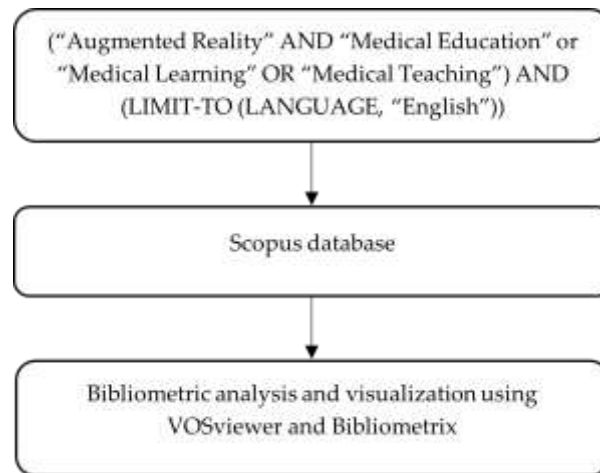


Fig 1. Methodology and Flow Diagram

## 3. Results and discussion

### 3.1. Analysis of global publication trends

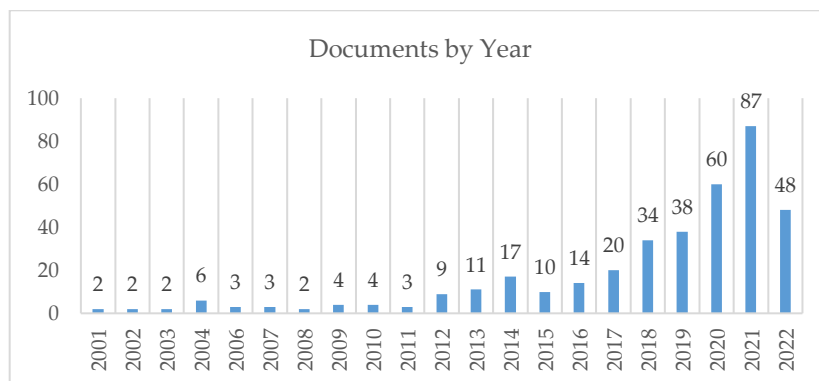


Fig. 2. Tendencies concerning augmented reality in medical education

Fig. 2 illustrates the research trends in AR and medical education. From the 379 papers that met our criteria, we found that research on AR in medical education started in 2001 and experienced rapid growth until August 15, 2022. The most significant growth occurred in 2021, with an increase of 27 publications (7.12%), and the highest number of publications on this topic, 87, also occurred in 2021 (22.95%). As of August 15, 2022, there were 48 publications (12.66%) in AR and medical education, and this trend is expected to continue. This upward trend in papers related to AR and medical education is associated with the onset of COVID-19, which began in early 2020.

### 3.2. Analysis of country/territory

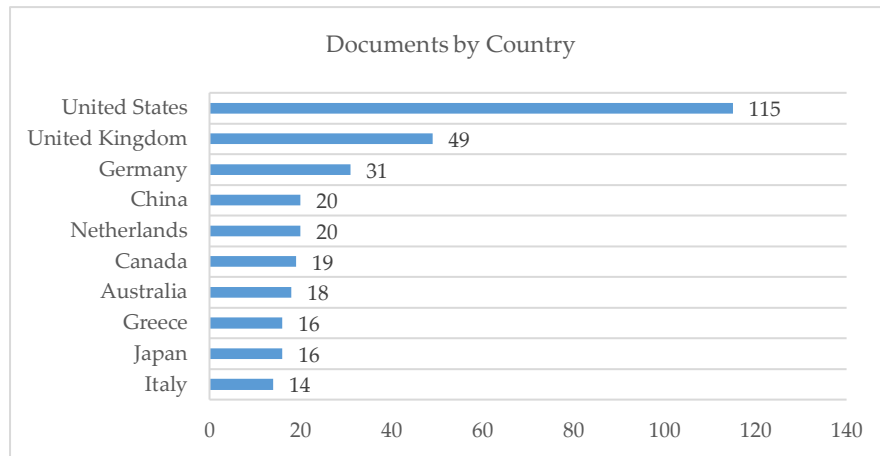


Fig. 3. Geographical distribution of nations performing research on augmented reality and medical education  
Fig. 3 depicts the distribution of nations conducting research and publishing articles on AR and medical education. The analysis revealed that the United States led with 115 publications (30.34%), making it the most prolific nation in this area. The United Kingdom followed closely behind with 49 articles (12.93%), securing the second position. Germany ranked third with 31 publications (8.18%).

The United States leads in publishing journals on this topic. According to Scimago Journal and Country Rank (SJR), the United States has the highest number of publications in the field of medicine, with 4,909,244 publications and the highest H-index of 1797. Similarly, the United States ranks first with an H-index of 530 for publications in health professions (<https://www.scimagojr.com/countryrank.php?area=2700>). This demonstrates that most research advancements in medicine and health professions originate from the United States.

Furthermore, the United States exhibits a rapid rate of technological advancement. According to Scimago Journal and Country Rank (SJR), the United States ranks first globally with 1,385,981 articles in Computer Science, including AR. The H-index for these publications is 1214, placing the United States at the forefront (<https://www.scimagojr.com/countryrank.php?area=1700>). Therefore, it can be stated that the United States leads in research development on AR applications in medical education. Previous studies also support this claim, indicating that the United States is the most prosperous country for AR and VR research and a leader in producing highly referenced AR and VR articles [2], [15], [20], [21].

#### Country Collaboration Map

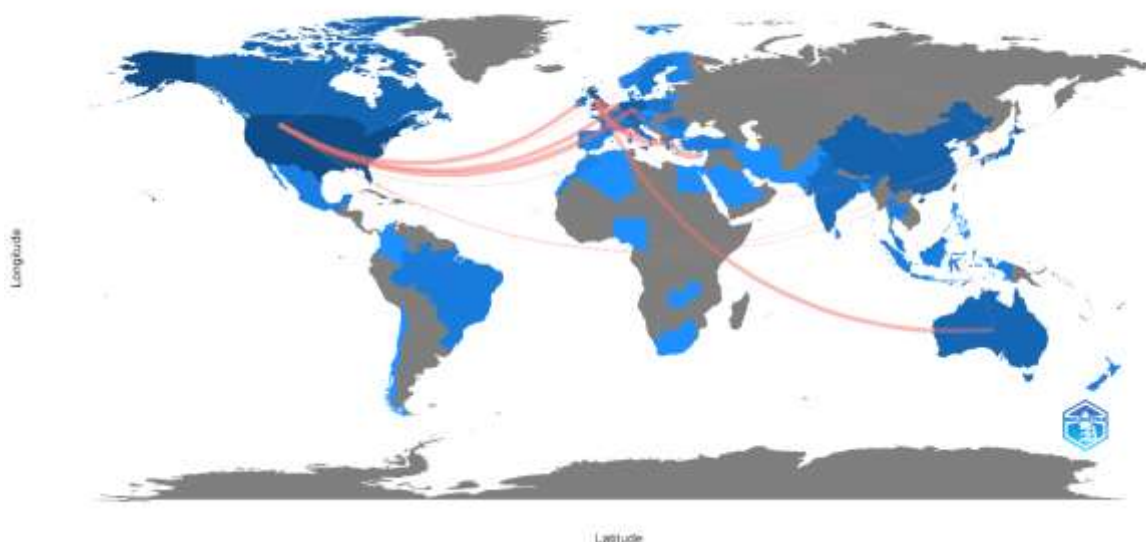


Fig. 4. Country collaboration map of researching augmented reality and medical education

Fig. 4 depicts the country collaboration in AR and medical education research. We can observe that the United States has the most extensive network compared to other nations, its dominance in this field.

The United States is the hub for AR and medical education research, with other countries pursuing AR and medical education research having a network with the United States.

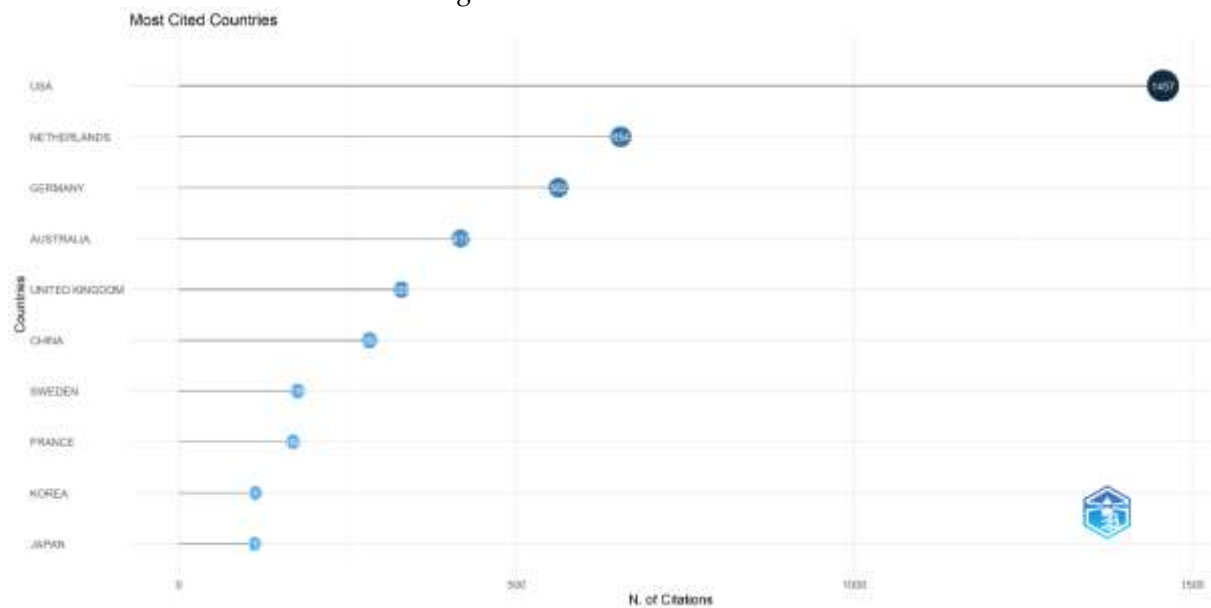


Fig. 5. Most cited countries for augmented reality and medical education research

Meanwhile, based on the number of countries with the most citations (Fig. 5), the United States maintains its top position as the most cited country in AR in medical education research. The Netherlands and Germany follow, ranking second and third, respectively.

### 3.3. Three-field plot analyses

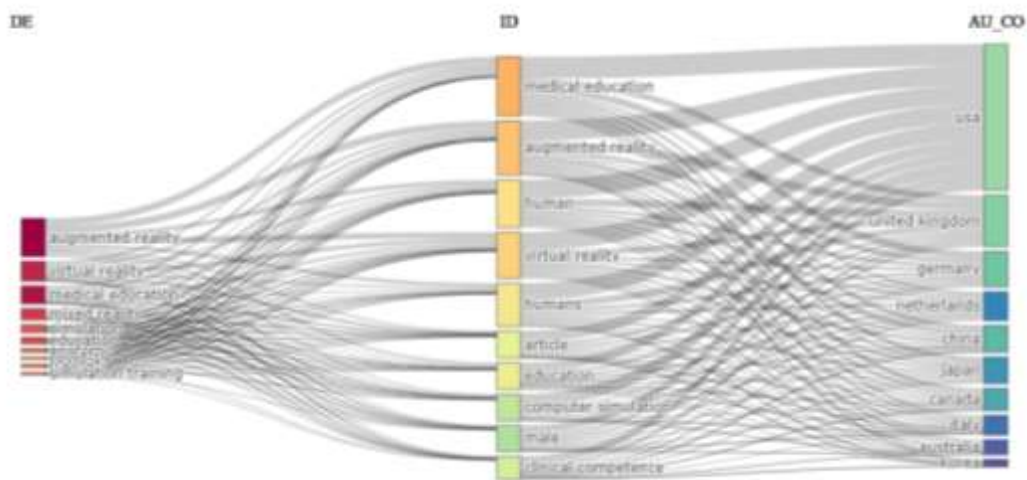


Fig. 6. A Three-field plot (Sankey Diagram) correlation of Keyword Plus, Author Keyword, and Country of publication in augmented reality and medical education

A three-field Plot (Sankey diagram) of Keyword Plus, Author Keyword, and Country of publication was developed to illustrate the distribution of research topics for each country. As shown in Fig 6, the analysis of keyword plus and author keyword indicates that the majority of papers discussing AR and medical education consent have been published in the United States (USA). The United Kingdom holds the second position, followed by Germany in third place.

### 3.4. Analysis of Journals

Out of the 379 publications that met our criteria, 260 journals examined the relationship between AR and medical education. Fig. 7 illustrates that the journal "Studies in Health Technology and Informatics" has published the most research on AR and medical education, with 19 articles (5.01%). This is followed by the "Anatomical Science Education" journal, which published 12 articles (3.16%). "Advances in



"Experimental Medicine and Biology" and "Surgical Endoscopy" journals, each with nine papers (2.37%), are in third place.

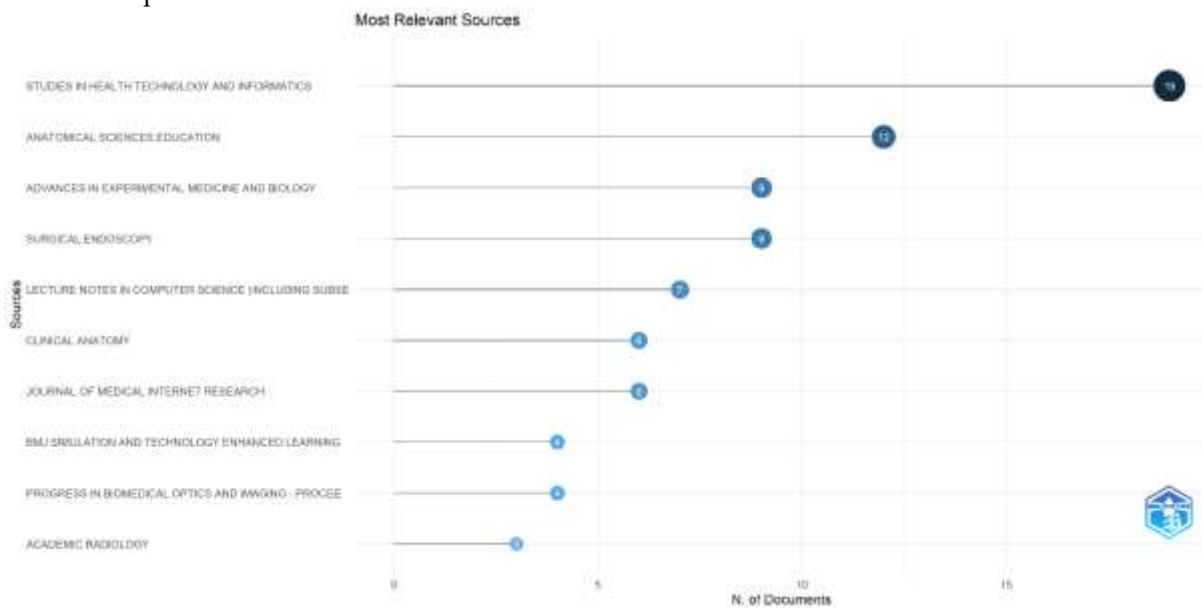


Fig. 7. The leading ten journals in augmented reality and medical education

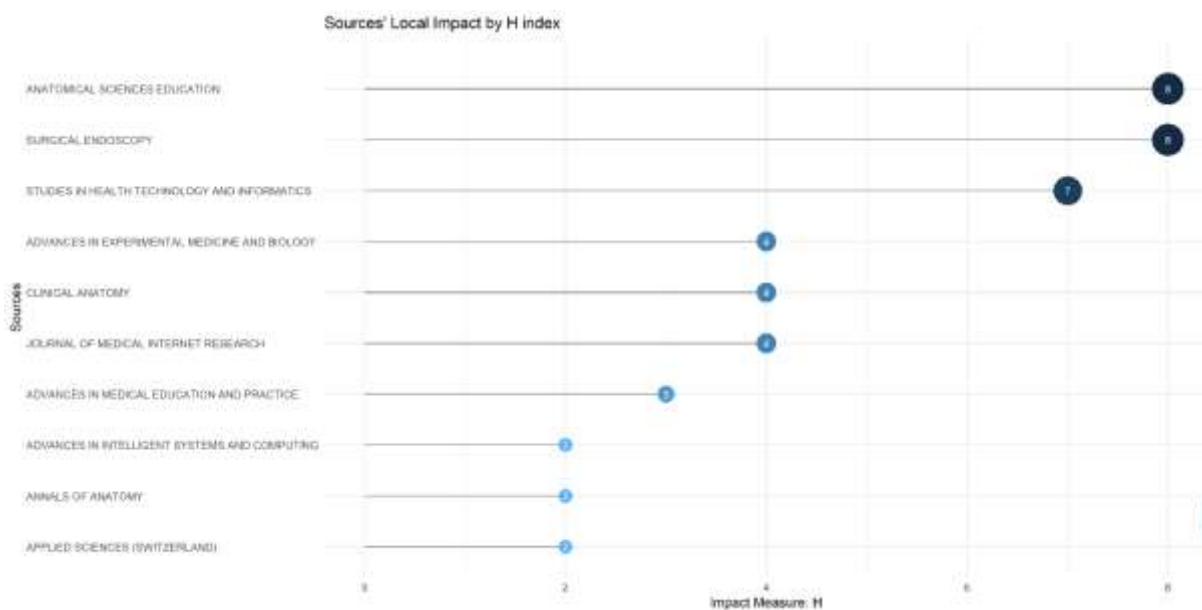


Fig. 8. The source's local impact by H-index

Meanwhile, based on the source's local impact by H-index (Fig 8), the "Anatomical Science Education" and "Surgical Endoscopy" journals have the highest H-index, namely 8. This indicates that these journals have received many citations to their articles.

### 3.5. Analysis of Influential Publications

Our investigation demonstrates that Scopus journals have a strong influence on citation-related metrics. A deeper analysis of table 1 reveals several trends and insights related to the domain of augmented reality (AR) in the context of medical education. Firstly, it is evident that the most cited article is "The Effectiveness of Virtual and Augmented Reality in Health Sciences and Medical Anatomy" by Moro et al. (2017), with 309 citations. This article provides a comprehensive review of the use of virtual and augmented reality in medical education and highlights the potential benefits of using these technologies. The popularity of this article reflects the growing interest in AR in medical education and the need for evidence-based research to support its effectiveness.

Table 1: The ten most valuable publications by citation weight

Rank	Authors	Title	Year	Source Title	Citations	References
1	Moro C., Štromberga Z., Raikos A., Stirling A.	The effectiveness of virtual and augmented reality in health sciences and medical anatomy	2017	Anatomical Sciences Education	309	[22]
2	Barsom E.Z., Graafland M., Schijven M.P.	Systematic review on the effectiveness of augmented reality applications in medical training	2016	Surgical Endoscopy	247	[23]
3	Küçük S., Kapakin S., Göktaş Y.	Learning anatomy via mobile augmented reality: Effects on achievement and cognitive load	2016	Anatomical sciences education	163	[24]
4	Pelargos P.E., Nagasawa D.T., Lagman C., Tenn S., Demos J.V., Lee S.J., Bui T.T., Barnette N.E., Bhatt N.S., Ung N., Bari A., Martin N.A., Yang I.	Utilizing virtual and augmented reality for educational and clinical enhancements in neurosurgery	2017	Journal of Clinical Neuroscience	162	[25]
5	Kamphuis C., Barsom E., Schijven M., Christoph N.	Augmented reality in medical education?	2014	Perspectives on Medical Education	151	[26]
6	Zhu E., Hadadgar A., Masiello I., Zary N.	Augmented reality in healthcare education: An integrative review	2014	PeerJ	144	[27]
7	Diana M., Marescaux J.	Robotic surgery	2015	British Journal of Surgery	139	[28]
8	Emanuel E.J.	The Inevitable Reimagining of Medical Education	2020	JAMA - Journal of the American Medical Association	118	[29]
9	Huang T.-K., Yang C.-H., Hsieh Y.-H., Wang J.-C., Hung C.-C.	Augmented reality (AR) and virtual reality (VR) applied in dentistry	2018	Kaohsiung Journal of Medical Sciences	92	[30]
10	Pfandler M., Lazarovici M., Stefan P., Wucherer P., Weigl M.	Virtual reality-based simulators for spine surgery: a systematic review	2017	Spine Journal	92	[31]

Secondly, table 1 shows that the top 10 articles were mostly published over the last five years, with the bulk appearing between 2014 and 2020. The increasing number of publications in recent years is likely due to the growing availability of AR technologies and the need for innovative approaches to medical education. The insights gained from this table can inform future research directions, advance emerging augmented reality (AR) technologies, and contribute to the transformation of medical education.

### 3.6. Analysis of Authors

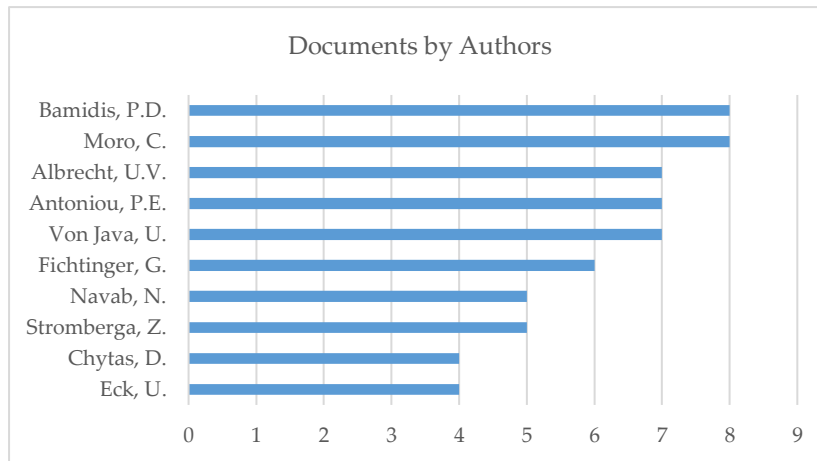


Fig 9. The authors' contribution to research on augmented reality in medical education

Among the 379 documents that meet our criteria (Fig 9), numerous authors have extensively studied this issue. First, Bamidis, P. D., and Moro, C., have made significant contributions to the study of AR applications in medical education, with eight titles each (2.11%).

Bamidis, P. D., has extensively researched AR in medical education, aligning with his background. He has published 429 Scopus-indexed works with 4954 citations and an H-index of 32 to date (<https://www.scopus.com/authid/detail.uri?origin=resultslist&authorId=6603398831&zone=>). In the meantime, Moro, C. has utilized various technological tools, including virtual and augmented reality, to boost student learning in his medical and biomedical classes. To date, Moro has published 35 Scopus-indexed documents with 711 citations and a 13-point H-index (<https://www.scopus.com/authid/detail.uri?origin=resultslist&authorId=53064362100&zone=>).

### 3.7. Analysis of Institutions

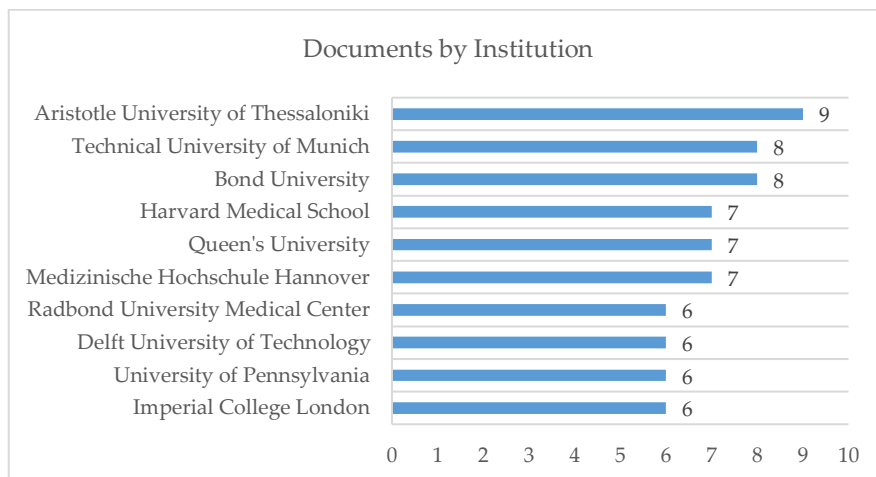


Fig. 10. The leading ten institutions contributing to augmented reality and medical education

According to the 379 documents that met our criteria, 160 institutions have authored articles on AR and medical education. Fig 10 shows that, out of these 160 institutions, Aristotle University of Thessaloniki has published the most papers on AR and medical education, with nine papers (2.37%). The Technical University of Munich and Bond University are tied for second place, with eight published articles each (2.11%).

### 3.8. Analysis of Main Topics

VOSviewer was utilized to extract the results (379 articles) based on the frequency of appearance of author keywords in bibliometric data. The minimum number of keyword occurrences was set at 3. Initially, we collected 800 keywords, but only 71 met the threshold. Information technology and three-dimensional printing were excluded as two popular terms that did not indicate a specific subject. In AR



and medical education, we identified five distinct color-coded clusters representing research topic trends.

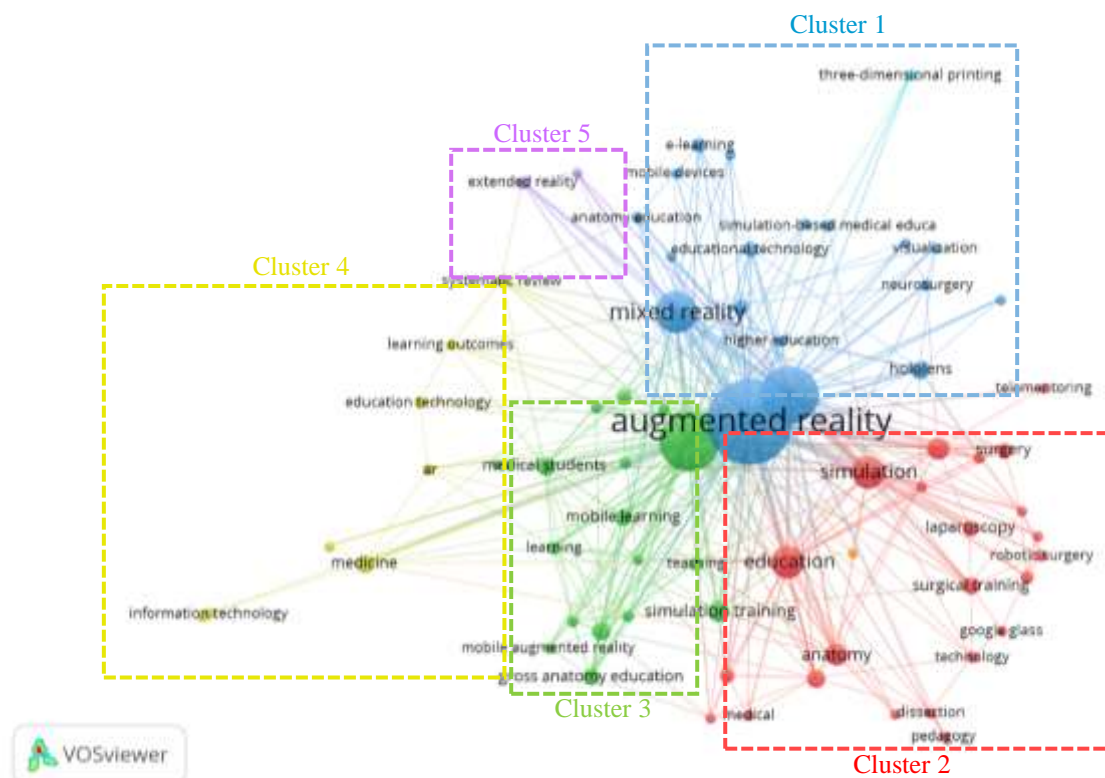


Fig. 11. Network visualization of Scopus database using VOSviewer

Fig 11 illustrates 5 clusters and their interrelationships within the investigated subject matter areas. In constructing the map, each group comprises several keywords that share a high degree of unity. Each group describes a specific (primary) issue as a study direction in AR and medical education based on its unique link with a set of keywords within the cluster. The cluster analysis of the terms highlights the different areas of focus in research on AR in medical education. Cluster 1, which has the most occurrence of terms, focuses on the various categories of reality technology, such as augmented reality, virtual reality, and mixed reality. These terms form the foundation of research and development in emerging advancements in medical education technology. Cluster 2 is concerned with the implementation of reality technology in medical education, with a focus on education, simulation, anatomy, training, surgery, and COVID-19. This cluster represents the most practical applications of reality technology in medical education, such as using simulation to train medical professionals and incorporating technology to adapt to the challenges posed by the pandemic.

Cluster 3 highlights the utilization of simulation training in the undergraduate medical students. and the incorporation of mobile learning in medical education. This cluster emphasizes the importance of incorporating technology in medical education at the undergraduate level to prepare students for the practical application of their knowledge. Cluster 4 focuses on systematic reviews and the assessment of learning outcomes in medical education technology. This cluster emphasizes the necessity of assessing the efficacy of reality technology in medical education to ascertain its impact on the educational achievements of medical students.

Finally, Cluster 5 focuses on the concept of extended reality, which comprises every reality technology, including augmented, virtual, and mixed reality. This cluster emphasizes the need for further research on the integration of all reality technologies in medical education. Overall, the cluster analysis shows that research on AR in medical education is a multidisciplinary field that encompasses technology, education, and medical training. The analysis highlights the need for collaboration between different disciplines to advance the development and application of reality technology in medical education.

3.9. Analysis of the most frequent topic and future research as potential topics

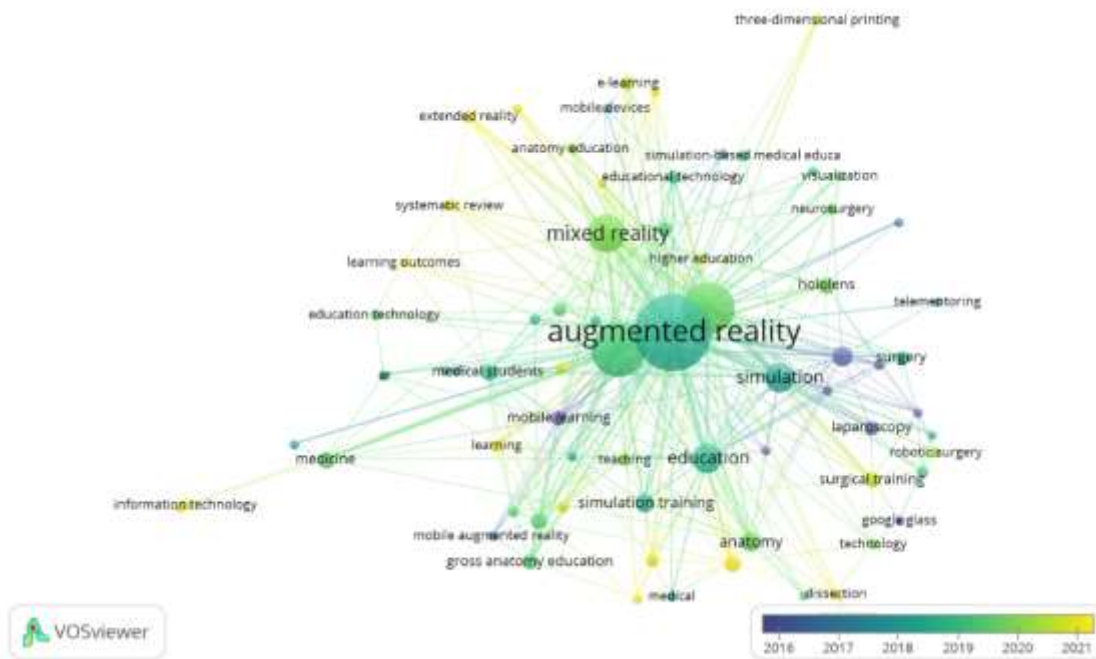


Fig. 12. Overlay visualization of Scopus database using VOSviewer

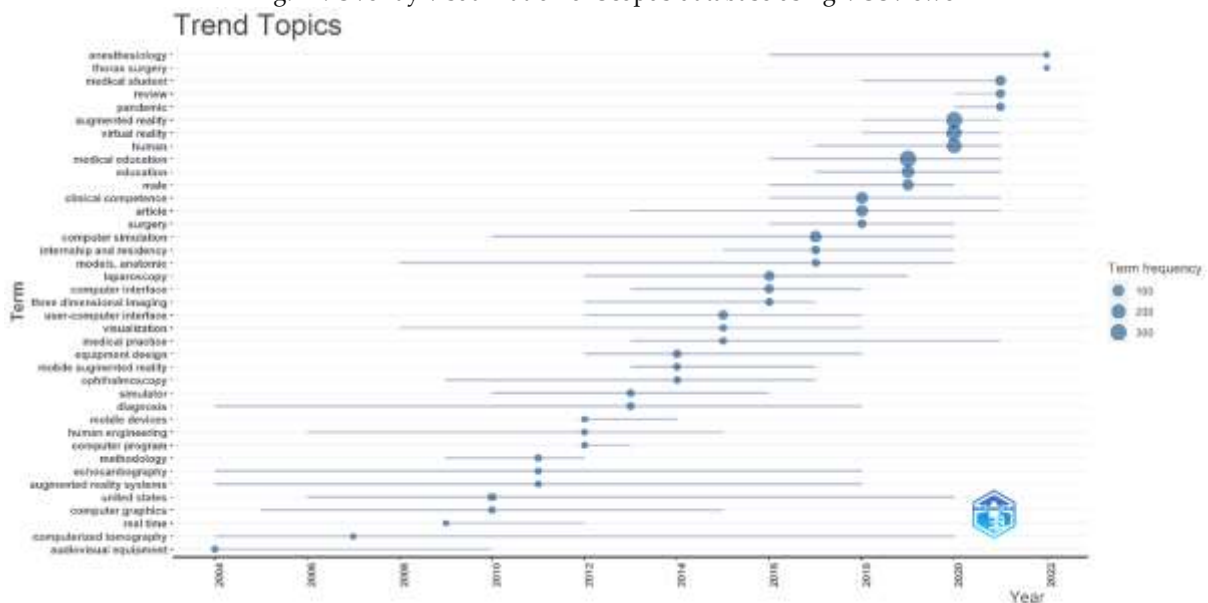


Fig. 13. Trend topics on augmented reality and medical education based on Bibliometrix

Fig 12 illustrates research topics by year, while Fig 13 depicts the visualization of trend topics using Bibliometrix, revealing the breadth of research conducted in AR and medical education. The size of the items determines the keywords' visibility in terms of frequency. Thus, smaller circles indicate keywords with less frequent occurrences, suggesting that the research topic is still limited and requires further study in the future (potential issue). Based on the analysis using VOSviewer, emergency medicine is one of the keywords that may represent potential concerns associated with augmented reality's application in medical education (Fig 14). Additionally, the analysis using Bibliometrix highlights keywords such as clinical skills training in anesthesiology and thorax surgery, which may represent several potential concerns associated with augmented reality's application in medical education (Fig. 13).

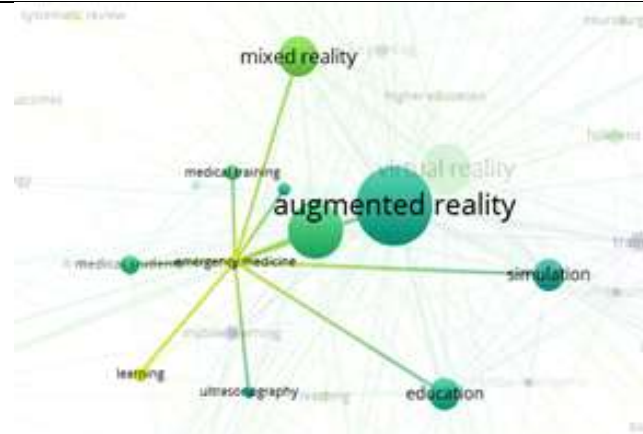


Fig 14. Overlay visualization of potential topics using VOSviewer

AR applications in the medical field include medical education, training, instruction, surgery, and post-medical therapy [32], [33]. In medical education, AR enables students to learn without time constraints and with greater flexibility. For example, in anatomy learning, students can observe the human body's structure in greater depth through augmented reality's presentation of three-dimensional imagery. This is unlike textbooks, which only provide two-dimensional representations that appear less detailed [22].

Moreover, medical students who received AR training showed improved learning and made fewer procedural errors during clinical skills training compared to those who received traditional training [32], [33]. AR provides a vastly superior user experience to virtual reality (VR) for clinical skills training [34]. Other studies show that AR also helps improve students' practice skills, such as blood transfusions and intradermal injections [35], endotracheal intubation, and central venous catheterization procedures [36]. In examinations such as the USMLE and MCAT, students who learn cardiac examination skills on a simulator outperform those trained on manikins [32].

AR offers additional benefits, such as allowing trainees to adjust their perspective for optimal viewing angles and to pause and rewind procedures to focus on specific steps [32], [37]. Moreover, it provides the freedom to practice without actual patients and machines, the flexibility of practicing at any time, and relatively affordable costs [38]. Based on these benefits, the application of AR to train students' clinical abilities is considered quite promising.

Based on a prior study, additional research is necessary on the development of AR in medical education, including the need to investigate long-term clinical consequences [39] and analyze the impact of AR training on the long-term knowledge and skill development of physicians [33]. Moreover, a previous study showed that mobile learning could be integrated with AR in the classroom. This is consistent with the results reported by Smith and Friel (2021), which indicated that most students desired additional AR models to be utilized in future lectures. These findings suggest that in the future, the medical curriculum should incorporate AR modules [40].

Based on the analysis using VOSviewer, as seen in Fig 13, the lighter the color, the more limited the research topic is and requires further study in the future. Emergency medicine is a keyword that tends to appear infrequently. This can be observed from the very small and light yellow-colored circle, indicating that the keyword emerged only at the end of 2020 or around 2021 and has not been extensively studied yet (Fig 14).

Emergency medicine is a domain and specialization that plays a crucial role in clinical decision-making and patient care, both in pre-hospital settings and emergency units. It continues to evolve and adapt in the context of patient care, encompassing the ability to adjust and modify approaches and practices within operating rooms, inpatient settings, training environments, and emergency care provision [41]. Due to its importance, technological advancements are being utilized for the development of this domain [41], [42].

In emergency medicine, the application of augmented reality (AR) is considered to provide medical assistance to emergency physicians in their daily practice, such as in pediatric emergency dose calculations [43]. AR is also deemed important for trauma evaluation and management; for example, through accelerometry measurements with the assistance of smart glasses, objective assessments of

concussion symptoms can be provided [44]. Additionally, in cases of disagreement between patients and healthcare professionals, AR is capable of elucidating relevant details and treatment strategies that are easy for patients to comprehend [42].

According to prior investigations, the use of augmented reality (AR) is expected to have a significant impact on the development of emergency medicine, particularly in providing care and education and training [41]. Several studies have demonstrated the capacity of augmented reality (AR) to bridge the gap between the skills required in real-life, intense, and demanding settings and instruction in simulated situations, enabling self-paced and affordable education, and enhancing student engagement in the educational process [42].

However, there are still limitations in the study results and evidence regarding the effectiveness of integrating augmented reality with self-learning [23], [42]. Considering the numerous benefits of augmented reality in assisting in achieving student understanding [40], further research is needed regarding its application in medical education. This further research is expected to focus on the analysis of long-term clinical consequences [39] and the impact of knowledge and long-term skill development of physicians through the utilization of augmented reality as the primary learning method [33].

Based on our investigation, we have determined that AR plays a significant role in enhancing medical students' comprehension. Therefore, its use in medical education must be continued. Furthermore, additional studies are necessary to establish the influence and development of AR in medical education. There is great optimism about using AR to supplement instructional content in medical education.

#### 4. Conclusions

Our study has analyzed research trends in the application of augmented reality (AR) in medical education. A bibliometric analysis was conducted on 397 articles obtained from the Scopus database to identify the most productive country/territory, journals, authors, and potential future topics in this research field. The study found that 2021 experienced the most significant growth. The United States of America emerged as the most productive nation in this field, with the *Studies in Health Technology and Informatics* being the most prestigious journal. The Aristotle University of Thessaloniki published the most papers in this field. The most cited article was "The Effectiveness of Virtual and Augmented Reality in Health Sciences and Medical Anatomy." Authors Bamidis, P. D., and Moro, C., made the most significant research contributions. The study also highlighted the need for further research in emergency medicine and clinical skills training in the future.

#### Author Contributions

A. A. N. N. Hanifah: Conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, visualization, writing – original draft, and writing – review & editing. S. Munawaroh: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, resources, supervision, validation, writing – original draft, and writing – review & editing. N. Wiyono: Conceptualization, formal analysis, funding acquisition, methodology, resources, software, supervision, validation, visualization, writing – original draft, and writing – review & editing. Y. Hastami: Conceptualization, funding acquisition, methodology, resources, supervision, validation, writing – original draft, and writing – review & editing. Z. Nuryana: Resources, supervision, validation, writing – original draft, and writing – review & editing. M. Muthmainah: Funding acquisition, resources, supervision, validation, writing – original draft, and writing – review & editing.

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#### Declaration of Competing Interest

We declare that we have no conflict of interest.

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