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Mixed, Augmented and Virtual Reality in STEM Education in The Context of Text Mining: A Bibliometric Map Analysis and Systematic Review

Oylum Çavdar[a], Bekir Yıldırım[b]*

[a,b] *Mus Alparslan University, Faculty of Education, Muş, Turkey*

Abstract

This paper conducted a systematic review and bibliometric map analysis to determine the current state of studies on mixed reality (MR), augmented reality (AR), and virtual reality (VR) in STEM education. The study focused on 477 scientific studies for bibliometric map analysis and 25 articles for systematic review. The bibliometric analysis showed that the most common keywords were "VR," "STEM education," "education," "STEM," "AR," and "MR." The most common words in the abstracts were "student," "technology," "STEM," "study," and "education." Johnson-Glenberg was the most cited author, while Computer & Education was the most cited journal. The systematic review showed that most studies recruited secondary and high school students. Most studies adopted quantitative research designs and employed surveys, knowledge tests, and self-efficacy and attitude scales. Most studies analyzed their data using inferential analysis methods. Some studies reported that AR, VR, and MR contributed to STEM education, whereas others did not. Some studies made recommendations for future studies regarding contributions to learners, program development, learning outcomes, comparison, and duration.

Keywords: Augmented reality; virtual reality; STEM education; bibliometric map analysis; systematic review

1. Introduction

Advances in science and technology have affected every sphere of life, from healthcare to finance. Facing those developments, countries have turned to new educational approaches because they need creative and tech-savvy citizens with critical thinking, cooperation, and problem-solving skills. One of those approaches is STEM education. Countries have integrated STEM education into their curricula to turn students into people with 21st-century skills and knowledge. However, STEM education is hard to deliver because it addresses abstract concepts and integrates different disciplines

* Corresponding author: Bekir Yıldırım. ORCID ID.: https://orcid.org/0000-0002-5374-4025
E-mail address: bekir58bekir@gmail.com

(Stohlmann et al., 2012). Therefore, countries have incorporated technology into their curricula to help students understand STEM-related abstract concepts and become interested in STEM fields (Hsu et al., 2017). Some of those technological tools are augmented reality (AR), virtual reality (VR), and mixed reality (MR) (Jiang et al., 2021; Lasika et al., 2020), which are integrated into various fields (Altmeyer et al., 2020; Faridi et al., 2020). These tools help students display high academic performance (Petrov & Atanasova, 2020), make informed STEM-related career choices (Jiang et al., 2021), develop self-efficacy (Shu & Huang, 2021), and comprehend abstract concepts (Chen et al., 2019). Researchers have performed further studies to better understand the contribution of those tools to education (Starr et al., 2019; Yannier et al., 2020). In recent years, some researchers have conducted systematic reviews to determine the learning outcomes of those tools (Ibanez & Delgado-Kloos, 2018; Mystakidis et al., 2021).

This study performed a systematic review and bibliometric analysis on publications on AR, VR, and MR in STEM education published between 2013 and 2021. There is a growing body of systematic reviews on AR in STEM education (Ajit et al., 2021; Ibanez & DelgadoKloos, 2018; Sarıkaya & Alsancak Sarıkay, 2020). However, no studies have addressed VR and MR in STEM education. Del Cerro Velazquez and Mendez (2021) conducted a systematic review on publications published in the Web of Science (WoS), Scopus, and Google Scholar databases between 2012 and 2020. Ajit et al. (2021) conducted a systematic review of publications published in the ScienceDirect database. Ibanez and Delgado-Kloos (2018) reviewed publications published in seven databases between 2010 and 2017. Mystakidis et al. (2021) conducted a systematic review on publications published in eight databases between 2010 and 2020. Sarıkaya and Alsancak Sarıkaya (2020) reviewed publications published in the WoS database between 2010 and 2018. This study focused on publications published in the WoS database between 2013 and 2021. The Web of Science was the database of choice because it is easy to access and has important indices (SSCI, SCI-E, etc.). This study reviewed publications that addressed AR, VR, and MR in STEM education between 2013 and 2022. There is a limited bibliometric analysis of publications on technological tools in STEM education (Talan, 2021). Moreover, there is no bibliometric analysis addressing all three technological tools (AR, VR, and MR) in STEM education. Therefore, this study conducted a bibliometric map analysis of publications examining AR, VR, and MR in STEM education.

This study will contribute to the literature and pave the way for further research on AR, VR, and MR in STEM education. This study conducted a systematic review and bibliometric map analysis to determine the current state of publications focusing on MR, AR, and VR in STEM education. The main research question was, “What is the current state of publications on MR, AR, and VR in STEM education?” The subquestions were as follows:

1. What methodologies do publications on AR, VR, and MR in STEM education adopt?
2. What sample populations and how large samples do publications on AR, VR, and MR in STEM education recruit?
3. What data analysis methods do publications on AR, VR, and MR in STEM education use?
4. What data collection tools do publications on AR, VR, and MR in STEM education use?
5. What are the results and recommendations of publications on AR, VR, and MR in STEM education?
6. What is the distribution of keywords in publications on AR, VR, and MR in STEM education?
7. What is the distribution of words in the abstracts of publications on AR, VR, and MR in STEM education?
8. Who are the most cited authors?
9. What journals are cited the most?

1.1. Literature review

1.1.1. Mixed Reality, Augmented Reality, and Virtual Reality as Educational Tools

New technological tools such as AR, VR, and MR improve education. Students move from the real world to the virtual world in different ways (Milgram & Kishino, 1994). Augmented reality is a fundamental technological tool used in every stage of education (Sarıkaya & Alsancak Sarıkaya, 2020; Hincapie et al., 2021). Augmented reality places digitalcontent on real scenes (Azuma, 1997). Virtual reality is the computer-assisted real-life visualization (Martín-Gutiérrez et al., 2017). Kayabaş (2005) defines virtual reality as a computer-generated 3D simulation that delivers a wide range of sensory information to the user to interact with objects in a virtual environment. Mixed reality is a more recent technology that delivers an expanded augmented reality experience (Doğan et al., 2021). These technological tools have numerous advantages. For example, they improve students' academic performance (Petrov & Atanasova, 2020) and help them understand abstract concepts (Arici et al., 2021). Therefore, those technological tools are integrated into physics (Faridi et al., 2021), museum (Huang et al., 2016), science (Huang, 2022), and math education (Lin et al., 2015). Those technological tools are also used in STEM education (Del Cerro Velazquez & Morales Mendez, 2021) because they are useful in the teaching of STEM fields (Ajit et al., 2021) and effective in STEM classes (Ibanez & Delgado-Kloos, 2018).

1.1.2. STEM Education

STEM education integrates science, technology, engineering, and math. Numerous countries implement STEM education in all stages of education because it helps students develop an interdisciplinary perspective and 21st-century skills, promotes research-based learning, and contributes to technological developments (Arslan, 2021). However, STEM education is hard to integrate into curricula because it consists of different disciplines and includes abstract concepts and engineering design processes (Stohlmann et al., 2012). Therefore, AR, VR, and MR are used by teachers to deliver STEM education (Sarıkaya & Alsancak Sarıkaya, 2020; Hsu et al., 2017).

2. Method

This study conducted a systematic review and bibliometric map analysis. The recruitment process was presented under separate headings.

2.1. Recruitment process

2.1.1. Recruitment for systematic review

The systematic review focused on publications published between 2013 and 2022. Articles can be recruited from different databases (Sarıkaya & Alsancak Sarıkay, 2020), such as EBSCOhost, ELSEVIER Scopus, JSTOR, ProQuest Dissertations & Theses, SAGE Premier Journals, Palgrave Macmillan Journals, SpringerLink, Taylor & Francis, Wiley, and Web of Science (WoS). This study recruited publications from WoS because it is easy to access and has important indices (SSCI, SCI-E, etc.). The sample consisted of 25 articles in English. The keywords were “augmented reality,” “virtual reality,” “mixed reality,” “STEM,” and “STEM education.” The database was screened using the advanced search option under the category of “education/education research.” The number of publications on AR, VR, and MR in STEM education was 248, 304, and 95, respectively (accessed: 23 Jan 2023). Each publication was analyzed according to specific criteria (See Table 1). As the first criterion, we checked whether the publications were about STEM education. As the second criterion, we checked whether the publications addressed AR, VR, and MR. Twenty-five articles published between 01.01.2013 and 31.12.2022 were included in the study.

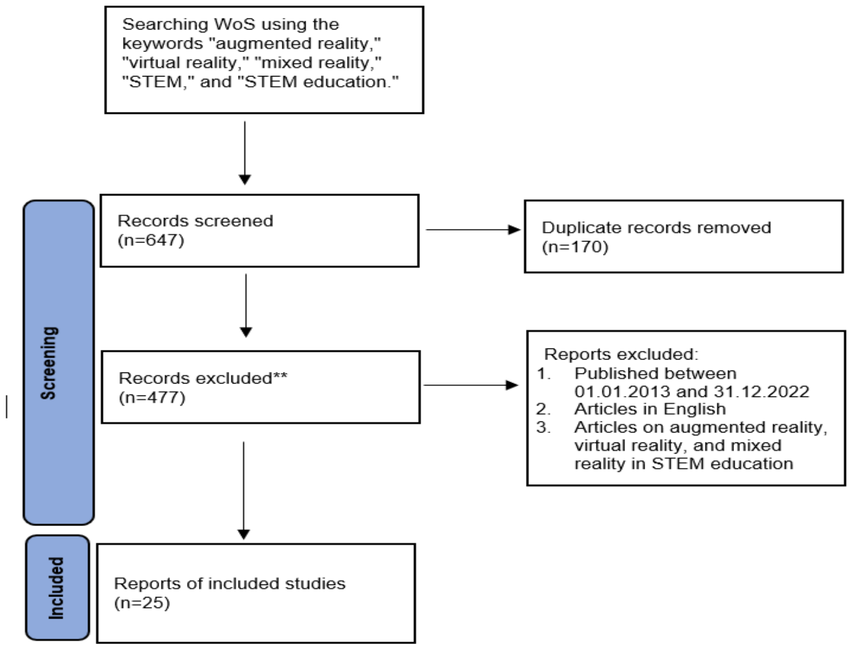


Figure 1. Recruitment process for systematic review

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Published in the WoS database	All scientific studies that did not meet the inclusion criteria were excluded.
Published between 01.01.2013 and 31.12.2022	
Articles	
English	
Articles on AR, VR, and MR in STEM education	

2.1.2. Recruitment process for bibliometric map analysis

Publications published in the Wos database between 2013 and 2022 were selected for the bibliometric map analysis. The database was searched using the keywords “augmented reality,” “virtual reality,” “mixed reality,” “STEM education,” and “STEM.” The number of publications on AR, VR, and MR in STEM education was 248, 304, and 95, respectively (accessed: 23 Jan 2023). Duplicates were removed. The sample for the bibliometric analysis consisted of 477 scientific publications (See. Figure 2). Afterward, each dataset was downloaded from WoS and analyzed using Vosviewer. The difference between the samples of the systematic review and bibliometric analysis was that the former consisted only of articles, whereas the latter consisted of all publications published between 2013 and 2022.

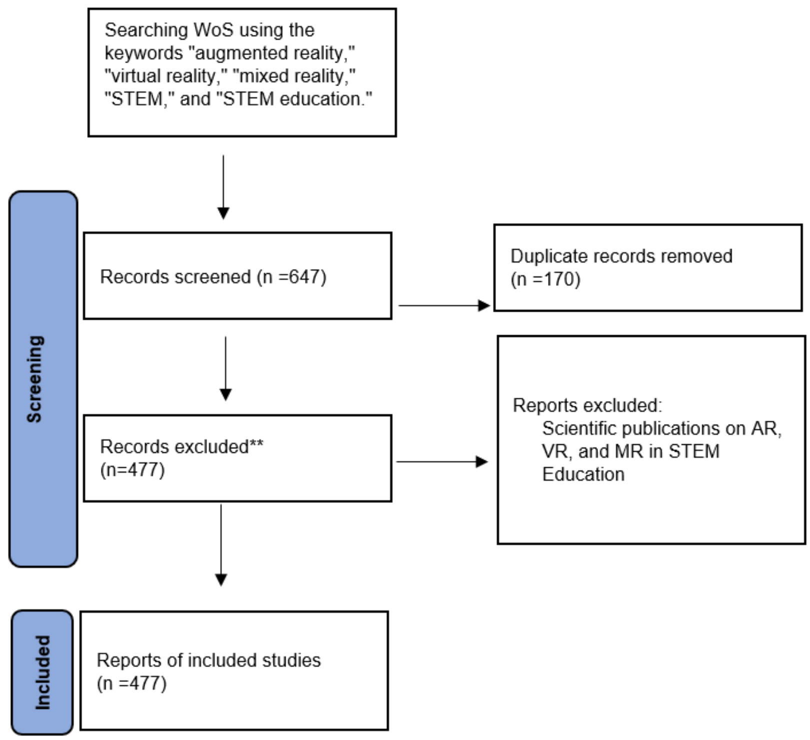


Figure 2. Scoping study selection

2.2. Data analysis

2.2.1. Semi-structured interview guide

The data were analyzed using the Educational Technologies Publication Classification Form (ETPCF) (Göktaş et al., 2012) the Technology Learning Model for Flipped Classrooms (Lin & Hwang, 2019), and key elements (Hareket & Kartal, 2021). Six subheadings were generated: (1) method, (2) data collection tools, (3) sample, (4) data analysis, (5) conclusion, and (6) recommendations. The data were analyzed using inductive content analysis, which involves coding data according to certain rules (Büyüköztürk et al., 2008). The study focused on the headings of “methodology,” “sample population and size,” “data collection tools,” “data analysis methods,” and “results and recommendations.” The results were presented in tables under these headings. Two experts analyzed and coded the data separately. Themes were developed out of the codes (Saldana, 2019). Bibliometric analysis was performed using Vosviewer, focusing on "the most common keywords," "the most common words in abstracts," "the most cited authors," and "the most cited journals." Two different experts created visual networks related to these variables. WoS data were analyzed separately on the Vosviewer program. As a result of the analysis, visual networks were interpreted and presented.

2.3. Credibility and consistency

Different methods were used for credibility and consistency. The data were collected from WoS. Continuous research was performed on WoS to avoid data loss (accessed: 23 Jan 2022; a double take: 12 Jun 2022). Two experts developed codes and themes to reduce researcher bias and ensure internal validity. Two experts also conducted the bibliometric analysis.

3. Results

3.1. Systematic review results

3.1.1. Methodology

The first research question focused on methodology. Figure 3 and Table 2 show the results.

Figure 3. Research methods

Most publications adopted quantitative research designs. Some publications employed qualitative, review/meta-analysis, and mixed research designs.

Table 2. Methodology

Theme	Category	Code	Sample research
Methodology	Quantitative	Experimental research (n=11)	(Shu & Huang, 2021)
	Qualitative	Case study (n=6)	(Jesionkowska et al., 2020)
	Mixed	Explanatory sequential design (n=3)	(Jiang et al., 2021)
	Other	Systematic/literature review (n=5)	(Ibanez & Delgado-Kloos, 2018)

Most publications adopted experimental research designs, followed by case studies, systematic/literature reviews, and explanatory sequential designs.

3.2. Sample population and size

The second research question addressed sample population and size. Tables 3 and 4 show the results.

Table 3. Sample size

Theme	Code	Sample research
Sample size	1-20 (n=4)	(Marques & Pombo, 2021)
	21-40 (n=4)	(Hsu et al., 2017)
	41-80 (n=11)	(Altmeyer et al., 2020)

	81-100 (n=1)	(Holly et al., 2021)
	101-199 (n=3)	(Chen et al., 2019)
	> 200 (n=2)	(Stojsıc et al., 2020)

The studies recruited samples of different sizes. Most studies recruited 41 to 80 participants.

Table 4. Sample group

Theme	Code	Sample research
Sample group	Secondary (5-12th grade) students (n=7)	(Chen et al., 2020)
	High school students (n=5)	(Mystakidis et al., 2021)
	Documents (n=5)	(Ajit et al., 2021)
	Teachers (n=3)	(Lasica et al., 2020)
	Primary (1-4th grade) students (n=1)	(Yannier et al., 2020)
	Preservice teachers (n=3)	(Holly et al., 2021)
	Undergraduate students (n=3)	(Starr et al., 2019)

*Including teachers and students

Most studies focused on secondary school students, high school students, and documents. Some studies focused on teachers, primary school students, preservice teachers, and undergraduates.

3.3. Data collection tools

The fourth research question investigated what data collection tools the articles used. Table 5 shows the results.

Table 5. Data collection tools

Theme	Category	Subcategory	Code	Sample research
	Qualitative data collection tools	Interview	Semi-structured interview (n=4)	(Cardullo & Wang, 2021)
			Focus group interview (n=2)	(Jiang et al., 2021)
		Observation	Observation (n=2)	(Lasica Et al., 2020)
		Document	Article (n=5)	(Ibanez & Delgado-Kloos, 2018)
		Questionnaire	Survey (open-ended questions) (n=9)	(Marques & Pombo, 2021)
	Quantitative data collection tools	Scale	Attitude scale (n=2)	(Stojsıc et al., 2020)
			Self-efficacy scale (n=3)	(Huang, 2022: 11 Jul

			2019)
		Alternative scales (n=7)	(Faridi et al., 2020)
	Test	Knowledge test (n=8)	(Shu & Huang, 2021)
		Alternative test tools (n=3)	(Starr et al., 2019))

The studies used different qualitative and quantitative data collection tools. Those that used quantitative data collection tools mostly used knowledge tests and alternative tests (critical thinking ability scale, etc.). Those that used qualitative data collection tools mostly used interview forms and questionnaires.

3.4. Data analysis methods

The fifth research question addressed data analysis methods. Table 6 shows the results.

Table 6. Data analysis methods

Theme	Category	Code	Sample research
Data analysis method	Inferential analyses	t-test (n= 11)	(Faridi et al., 2020)
		ANOVA/ANCOVA (n= 5)	(Shu & Huang, 2021)
		Correlations (n= 3)	(Sung et al., 2021)
		Effect size (Cohen's d) (n= 3)	(Huang, 2022: online first: 2019)
		Regression (n= 2)	(Starr et al., 2019)
		Exploratory factor analysis (n= 2)	(Holly et al., 2021)
		Non-parametric tests (n= 1)	(Stojsıc et al., 2020)
		MANOVA/MANCOVA (n= 1)	(Altmeyer et al., 2020)
		Eta-square (n= 1)	(Stojsıc et al., 2020)
		Alternative analyses (Person's chi-square, Cronbach's alpha, matrix, etc.) (n= 5)	(Chen et al., 2020)
	Qualitative Analyses	Content analyses (n= 12)	(Sarıkaya & Alsancak Sarıkay, 2020)
		Descriptive analyses (n= 5)	(Marques & Pombo, 2021)
	Descriptive	Means, standard deviations, frequencies, etc. (n= 14)	(Starr et al., 2019)

analyses	Graphs (n= 8)		(Ajit et al., 2021)

Most studies used inferential analyses, followed by qualitative and descriptive analyses. Moreover, the studies used different types of analysis.

3.5. Results and recommendations

The sixth research question focused on results and recommendations. Tables 7 and 8 show the results.

Table 7. Results

Theme	Category	Subcategory	Code	Sample research
Positive Results		Contribution to the learner	Increasing interest/motivation (n=10)	Jiang et al., 2021
			Acquiring knowledge (n=8)	Chen et al., 2019
			Accelerating the learning process (n= 5)	Altmeyer et al., 2020
			Helping develop skills (n= 5)	Faridi et al., 2021
			Developing attitudes (n= 4)	(Stojsıc et al., 2020)
			Increasing academic performance (n= 4)	Del Cerro Velazquez & Mendez, 2021
			Helping develop spatial skills (n= 2)	Del Cerro Velazquez & Mendez, 2021
			Helping develop self-efficacy (n= 2)	Shu & Huang, 2021
			Providing interdisciplinary teaching (n= 1)	Shu & Huang, 2021
			Reducing the threat of stereotypes (n= 1)	(Starr et al., 2019)
			Improving academic perception (n= 1)	
			Improving STEM knowledge (n= 1)	Jesionkowaska et al., 2020
			Helping develop hands-on skills (n= 1)	Chen et al., 2019
		Educational outcomes	Fun learning (n= 1)	Jesionkowaska et al., 2020
			Visualization (n= 2)	Stojsic et al., 2021
			Learning at desired time, space etc. (n= 1)	Sarıkaya & Alsancak Sarıkaya, 2020
			Student-centered learning (n= 1)	Sarıkaya & Alsancak Sarıkaya, 2020
			Meaningful/deep learning (n= 2)	Ajit et al., 2021
			Promoting science learning (n= 1)	Yannier et al., 2020
			Putting knowledge into practice (n= 1)	Yannier et al., 2020
		Results for students	Ensuring the professional development of teachers (n=3)	Marques & Pombo, 2021
			Helping develop positive views on the use of technological tools, such as AR, VR, etc. (n=1)	Cardullo &Wang, 2022

		Helping integrate technological tools, such as Ar, VR, etc. into lectures (n=1)	Lasica et al., 2020
		Motivating teachers (n=1)	
Negative Results	Contribution to the learner	Helping develop science self-efficacy (n= 1)	Huang, 2022
		Improving knowledge-based performance (n= 1)	Sung et al., 2021
	Educational outcomes	No relationship between academic performance and science self-efficacy (n= 1)	Huang, 2022

The studies reported different results. They stated that AR, VR, and MR in STEM education facilitated the learning process, helped students acquire knowledge and develop 21st-century skills, promoted science learning, and made learning fun. Some studies reported that AR, VR, and MR in STEM education had no positive effects.

Table 8. Recommendations

Theme	Category	Code	Sample research
	Student	Impact on student attitudes (n= 2)	Stojsic et al., 2021
		Using them to develop STEM skills (n= 1)	Jesionkowaska et al., 2020
		Using them to develop 21st-century skills (n=1)	Lasica et al., 2020
		Developing spatial intelligence (n=1)	Del Cerro Velazquez & Mendez, 2021
		Using them to develop self-interventions (n= 1)	Starr et al., 2019
	Teacher	Technology literacy should be promoted (n=2)	Cardullo &Wang, 2022
		Organizing training on using technological tools (n=2)	Marques & Pombo, 2021
		Investigating barriers to professional development (n=1)	
		Developing open access resources for teachers (n=2)	Del Cerro Velazquez & Mendez, 2021

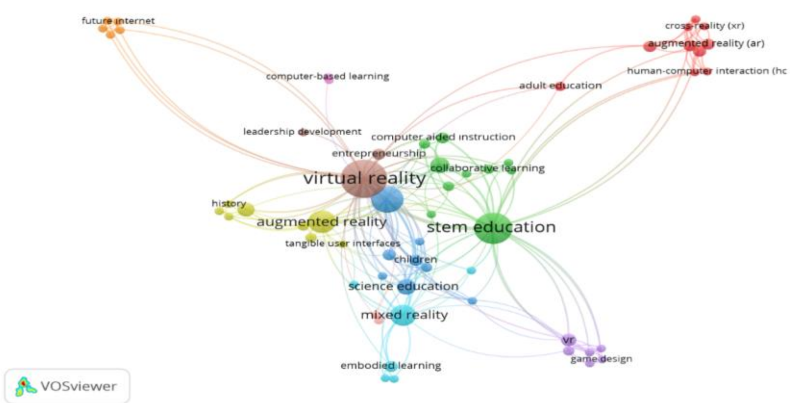
Program development	Developing pedagogical models for schools (n= 1)	Holly et al., 2021
	Developing learning activities (n= 2)	Del Cerro Velazquez & Mendez, 2021
Educational outcomes	Using them to teach STEM fields (n= 6)	Mystakidis et al., 2021
	Using them for effective learning environments (n= 3)	Faridi et al., 2021
	Using them to support STEM learning (n= 2)	Ibanez & Delgado-Kloos, 2018
	Using them to promote STEM career choices (n=1)	Jiang et al., 2021
	Using them to reduce the threat of stereotypes (n= 1)	Starr et al., 2019
	Facilitating interdisciplinary teaching (n= 1)	Chen et al., 2020
Comparison	Comparing the views and attitudes of teachers and students towards the use of AR (n= 1)	Stojsic et al., 2021
	Exploring the interaction between self-efficacy and career backgrounds and VR content (n=1)	Jiang et al., 2021
Educational environment	Using them in informal educational settings (n=1)	Sarıkaya & Alsancak Sarıkaya, 2020
Simple	Working on different groups (disadvantaged students, large samples, etc.) (n= 2)	
Material	Using them to support out-of-class activities in the flipped learning method (n=1)	
	Using additional resources in the process (n= 1)	Sung et al., 2021
	Creating online teaching content (n= 1)	Faridi et al., 2021
	Supporting education with software developed by technology companies (n=1)	Cardullo &Wang, 2022
	Using VR and AR in STEM education (n= 3)	Starr et al., 2019
	Using different technologies (VR, zSpace, 5G, etc.) to enhance learning (n= 3)	Chen et al., 2019
	Conducting qualitative meta-synthesis studies on technological tools (n=1)	Del Cerro Velazquez & Mendez, 2021
	Using Geogebra AR apps (n= 1)	

	Using Geogebra AR in math education (n=1)	
	Cost reduction (n=1)	Huang, 2022
	Using mobile VR (n= 2)	Holly et al., 2021

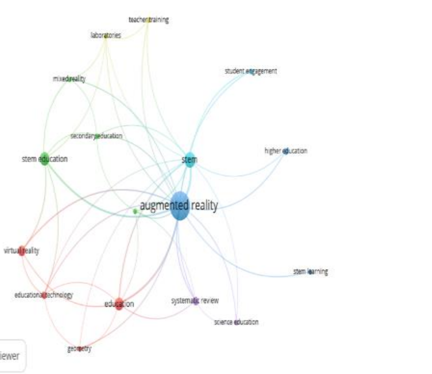
The studies made different recommendations regarding students, teachers, program development, educational outcomes, comparison, sample, and material.

3.6. Bibliometric map analysis

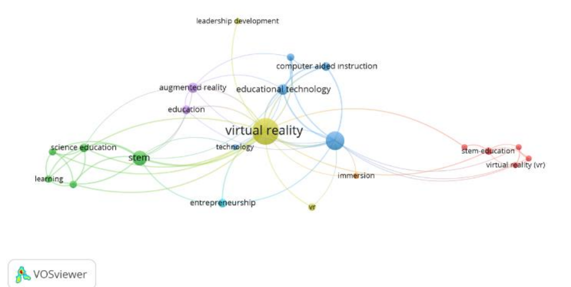
The seventh research question investigated the distribution of keywords. Figure 4 shows the results.



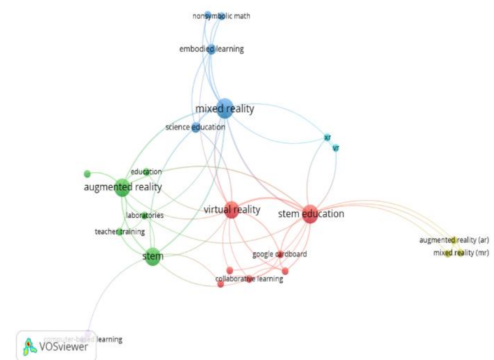
A- Keywords of studies on AR, VR, and MR in STEM education



. Keywords of studies on AR in STEM education



C- Keywords of studies on VR in STEM education



D- Keywords of studies on MR in STEM education

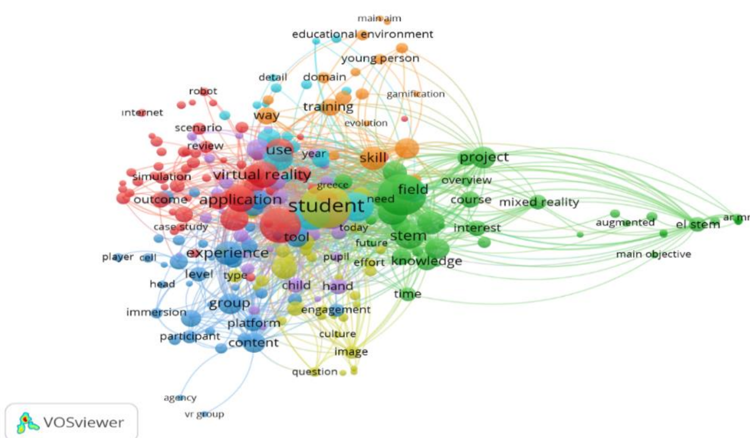
Figure 4. Keywords of studies on AR, VR, and MR in STEM education

Bibliometric maps were created for the most common keywords. Although the minimum number of repeats of a keyword is automatically determined as 5 in a bibliometric map, the minimum number of repeats was determined as 2 in this study.

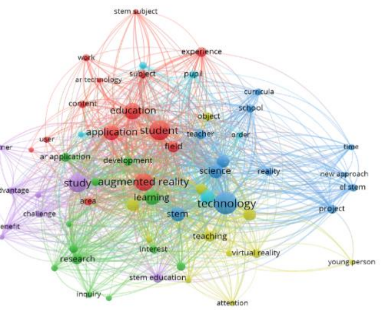
The number of clusters for AR, VR, and MR in STEM education was 6, 7, and 4, respectively. The most common keywords in the studies on AR in STEM education were "AR (f=44)," "STEM (f=13)," "STEM education (f=10), and "education (f=9)" (Figure 4-B). The most common keywords in the studies on VR in STEM education were "VR (f=35)," "STEM education (f=18)," "STEM (f=11)," and "educational technology (f=11)" (Figure 4-C). The most common keywords in the studies on MR in STEM education were "MR (f=14)," "STEM education (f=12)," "STEM (f=11)," "AR (f=11)," and "VR (f=10)" (Figure 4-D). All in all, the most common keywords in the studies on AR, VR, and MR in STEM education were "education," "STEM education," "STEM," "reality," "AR," "VR," and "MR." A bibliometric map was created for the most common keywords in the studies on AR, VR, and MR in STEM education (Figure 4-A). The most common keywords in the studies on AR, VR, and MR in STEM education were also "VR (f=45)," "STEM education (f=30)," "STEM (f=22)," "AR (f=16)," and "MR (f=14)."

3.6.1. The most common words in abstracts

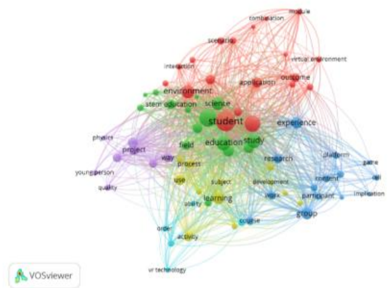
The eighth research question examined the distribution of the words in the abstracts of the studies on AR, VR, and MR in STEM education. Figure 5 shows the results.



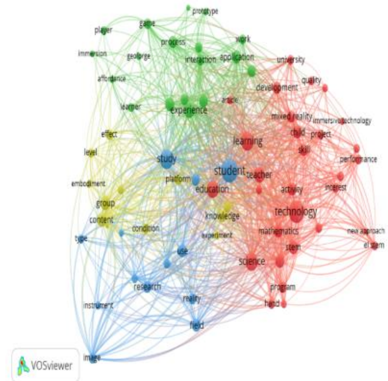
A- The words in the abstracts of studies on AR, VR, and MR in STEM education



B- The words in the abstracts of studies on AR in STEM education



C- The words in the abstracts of studies on VR in STEM education



D- The words in the abstracts of studies o education

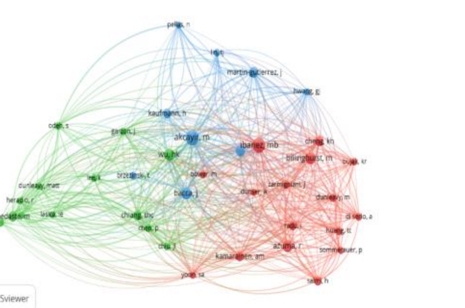
Figure 5. A bibliometric analysis of the words in the abstracts of studies on AR, VR, and MR in STEM education

Bibliometric maps were created for the most common words in the abstracts. Although the minimum number of repeats of a word is automatically determined as 10 in a bibliometric map, the minimum number of repeats was determined as 5 in this study. The number of clusters for AR, VR, and MR in STEM education was 6, 6, and 3, respectively. The most common words in the abstracts of the studies on AR in STEM education were "technology (f=78)," "student (f=64)," "study (f=54)," "AR (f=50)," and "education (f=44)" (Figure 5-B). The most common words in the abstracts of the studies on VR in STEM education were "student (f=87)," "technology (f=69)," "VR (f=55) "study (f=46)," and "education (f=44)" (Figure 5-C). The most common words in the abstracts of the studies on MR in STEM education were "student (f=66)," "technology (f=58)," "study (f=45)," "learning (f=40)," and "science (f=37) (Figure 5-D). All in all, the most common words in the abstracts of the studies on AR, VR, and MR in STEM education were "student," "technology," "education," "study," "AR," "VR," "learning," and "science." A bibliometric map was created for the most common words in the abstracts of the studies on AR, VR, and MR in STEM education (Figure 5-A). The most common words in the abstracts of the studies on AR, VR, and MR in STEM education were also "student (f=207)," "technology (f=30)," "STEM (f=183)," "study (f=137)," and "education (f=105)."

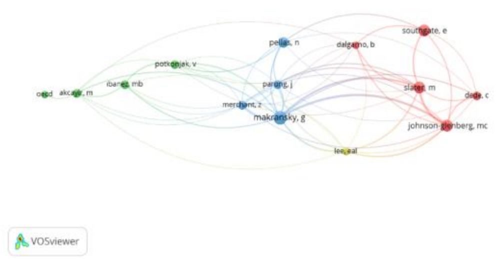
3.6.2. The most cited authors

The ninth research question addressed the distribution of the most cited authors. Figure 6 shows the results.

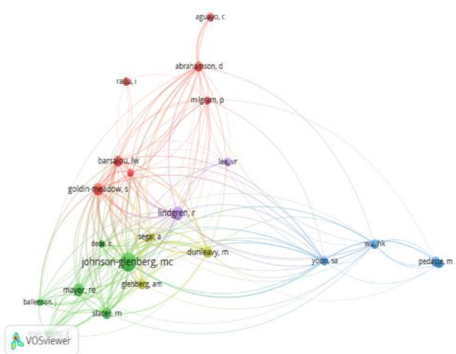
A- The most cited authors of studies on AR, VR, and MR in STEM education



B- The most cited authors of studies on AR in STEM education



C- The most cited authors of studies on VR in STEM education



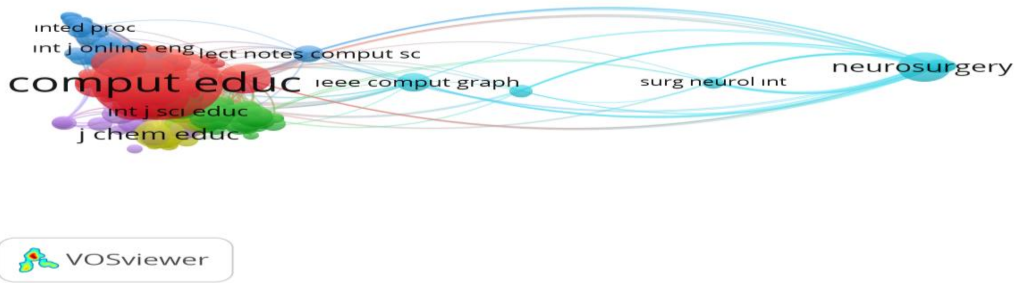
D- The most cited authors of studies on MR in STEM education

Figure 6. The most cited authors of studies on AR, VR, and MR in STEM

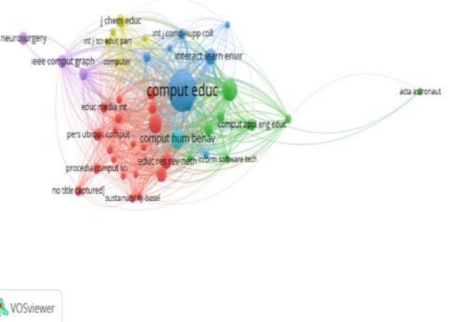
Co-citation analysis and cited authors were selected to create a bibliometric map for the most cited authors. The minimum number of citations was five (Figure 5). The most cited authors of the studies on AR in STEM education were Akçayır (f=23), Ibonez (f=21), and Wu (f=14) (Figure 6-B). The most cited authors of the studies on VR in STEM education were Makransky (f=10), Johnson-Glenberg (f=11), Slater (f=11), and Southgate (f=11) (Figure 6-C). The most cited authors of the studies on MR in STEM education were Johnson-Glenberg (f=29), Lindgren (f=15), and Mayer (f=14) (Figure 6-D). A bibliometric map was generated for all studies on AR, VR, and MR in STEM education (Figure 6-A). According to the bibliometric analysis, the most cited authors were Johnson-Glenberg (f=40), Akçayır (f=34), Ibonez (f=31), Makransky (f=25), and Wu (f=25).

3.6.3. The most cited journals

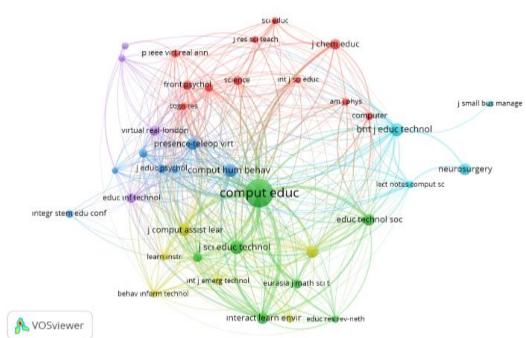
The tenth research question focused on the most cited journals. Figure 7 shows the results.



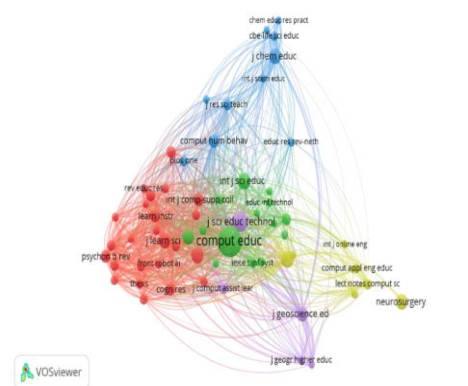
A- The most cited journals regarding studies on AR, VR, and MR in STEM education



B- The most cited journals regarding studies on AR in STEM education



C- The most cited journals regarding studies on VR in STEM education



D- The most cited journals regarding studies education

Figure 7. The most cited journals regarding studies on AR, VR, and MR in STEM

Co-citation analysis and cited sources were selected to generate a bibliometric map for the most cited journals. The minimum number of citations was five (Figure 7). The most cited journals regarding the studies on AR in STEM education were Computers & Education (f=139), Journal of Science Education and Technology (f=39), and Computers in Human Behavior (f=31) (Figure 7-B). The most cited journals regarding the studies on VR in STEM education were Computers & Education (f=87), Journal of Science Education and Technology (f=21), Computers in Human Behavior (f=18), and British Journal of Educational Technology (f=18) (Figure 7-C). The most cited journals regarding the studies on MR in STEM education were Computers & Education (f=72), Journal of Science Education and Technology (f=31), International Journal of Science Education (f=21), and British Journal of Educational Technology (f=20) (Figure 7-D). A bibliometric map was generated for all studies on AR, VR, and MR in STEM education (Figure 7-A). According to the bibliometric analysis, the most cited journals were Computers & Education (f=298), Journal of Science Education and Technology (f=91), Computers in Human Behavior (f=63), Educational Technology and Society (f=55), and British Journal of Educational Technology (f=51).

4. Discussion and Conclusion

This study conducted a systematic review and bibliometric map analysis to identify the current state of studies on AR, VR, and MR in STEM education.

The first research question focused on methodology. Most studies on AR, VR, and MR in STEM education employed quantitative research designs (e.g., Shu & Huang, 2021), followed by qualitative research designs (e.g., Cardullo & Wang, 2021), reviews/metasynthesis (e.g., Ajit et al., 2021), and mixed research designs (Stojsic et al., 2021). The studies that employed quantitative research designs used semi-experimental methods, while those that employed qualitative research designs adopted a case study. The studies that employed mixed research designs supported quantitative data with qualitative data. Most studies used quantitative research designs (Arici et al., Kucuk et al., 2013; Ibanez & Delgado-Kloos, 2018). For example, Pellas et al. (2020) found that most studies on VR in STEM education used quantitative research designs. Our results are consistent with the literature.

The second research question addressed sample population and size. Most studies recruited secondary school students, high school students (Stojsic et al., 2020), and documents (e.g., del Cerro Velazques, 2021), followed by teachers, primary school students (e.g., Yannier et al., 2020), preservice teachers (Holly et al., 2021), and undergraduates (Starr et al., 2019). Sarıkaya and Sarıkaya (2020) also reported similar results. Moreover, the samples of the studies consisted of 41 to 80 people. Our results are consistent with the literature.

The third research question investigated what data collection tools the studies on AR, VR, and MR in STEM education used. The studies that used qualitative data collection tools mostly used interview forms (e.g., Cardullo & Wang, 2021), surveys (open-ended questions) (e.g., Lasica et al., 2020), and documents (Ibanez & Delgado-Kloos, 2018). The studies that used quantitative data collection tools mostly employed scales (self-efficacy, attitude, pSTEM motivation, etc.) and tests (knowledge test, makerspace test, etc.).

The fourth research question looked into the data analysis methods employed by the studies on AR, VR, and MR in STEM education. Most studies used predictive analysis, followed by qualitative and descriptive analysis. The studies that used predictive analysis used t-test, ANOVA/ANCOVA, effect size, and correlation. The studies that used qualitative analysis analyzed data using content analysis. The studies that used descriptive analysis analyzed data using variables, such as mean and standard deviation. Our results are consistent with the literature (Altmeyer et al., 2020; Arici et al., 2021; Pellas et al., 2020; Sung et al., 2021; Yannier et al., 2020). Some studies employed qualitative analysis methods (Cardullo & Wang, 2022; Lasica et al., 2020; Marques & Pombo, 2021).

The fifth research question examined the results and recommendations of the articles on AR, VR, and MR in STEM education. The results of the articles showed that using AR, VR, and MR in STEM education helped students acquire conceptual knowledge (Altmeyer et al., 2020), develop spatial (Del Cerro Velazquez & Mendez, 2021) and critical thinking skills (Faridi et al., 2020), and make informed career choices in STEM fields (Jiang et al., 2021).

The articles also reported that using AR, VR, and MR in STEM education improved students' academic performance (Petrov & Atanasova, 2020) and made them more interested in STEM fields (Hsu et al., 2017). Many studies show that using AR, VR, and MR in STEM education has positive effects (Ajıt et al., 2021; Chen et al., 2019; Ibáñez & Delgado-Kloos, 2018; Sarıkaya & Alsancak Sarıkaya, 2020). The articles also made recommendations regarding teachers, students, program development, educational outcomes, comparison, sample, and material. Our results are consistent with the literature.

The sixth research question focused on the bibliometric analysis of the distribution of the keywords of the articles on AR, VR, and MR in STEM education. The bibliometric analysis showed that the most common keywords were "VR," "STEM education," "STEM," "AR," and "MR." Talan (2021) conducted a bibliometric analysis of studies on AR in STEM education and found that the most common keywords were "AR," "VR," "mobile learning," "science education," and "MR." Arici et al. (2021) focused on studies on AR in science education and reported that the most common keywords were "AR," "mobile learning," "science education," "science learning," and "e-learning." Özkaya (2019) determined that the most common keywords were "education," "STEM," "science," "student," and "STEM education." Our results are consistent with the literature The seventh research question looked into the bibliometric analysis of the distribution of words in the abstracts of the articles on AR, VR, and MR in STEM education. The bibliometric analysis showed that the most common words were "student," "technology," "STEM," "study," and "education." Our results are consistent with the literature (Arici et al., 2021; Özkaya, 2019; Talan, 2021).

The eighth research question focused on the bibliometric analysis of the most cited authors of the articles on AR, VR, and MR in STEM education. The bibliometric analysis showed that the most cited authors were Johnson-Glenberg, Akçayır, Ibonez, Makransky, and Wu. Talan (2021) conducted a biometric analysis of studies on AR in STEM education and reported similar results. Arici et al. (2021) focused on studies on AR in science education and found that Azuma and Wu were the most cited authors. Our results are consistent with the literature.

The ninth research question focused on the bibliometric analysis of the most cited journals that published articles on AR, VR, and MR in STEM education. The bibliometric analysis showed that the most cited journals were Computers and Education, Journal of Science Education and Technology, Computers in Human Behavior, Educational Technology and Society, and British Journal of Educational Technology. These journals publish articles on technology in education (Arici et al., 2021). They have also published systematic reviews on AR (Arici et al., 2021; Ibanez & Delgado-Kloos, 2018; Talan, 2021). For example, Arici et al. (2021) conducted a bibliometric analysis on the studies on AR in science education and reported similar results. Our results are consistent with the literature.

5. Recommendations for Future Studies

This study recruited publications from the WoS database. Researchers should focus on different databases and recruit publications on AR, VR, and MR in STEM education published between 2013 and 2022. The sample of this study consisted of articles. Researchers should focus on different types of documents. The publications on AR, VR, and MR in STEM education made different recommendations. Researchers should consider those recommendations before they conduct research. For example, AR, VR, and MR can make students more interested in STEM fields and break their stereotypes regarding STEM education. Our results showed that few publications on AR, VR, and MR in STEM education employed mixed research designs. More studies should use mixed research designs in the future.

6. Limitations

This study had three limitations. First, the sample consisted of publications published between 01.01.2013 and 31.12.2022. Second, the publications were recruited from one database. Third, the systematic review part of the study focused only on articles.

7. Funding

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8. Competing or Conflict of interests

The authors declare they have no competing or conflict of interests.

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