European Journal of Science and Mathematics Education, 2023, **11**(3), 556-572
ISSN: 2301-251X (Online)

OPEN ACCESS

Review Article

A systematic literature review on augmented reality in mathematics education

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Citation: Bulut, M., & Borromeo Ferri, R. (2023). A systematic literature review on augmented reality in mathematics education. *European Journal of Science and Mathematics Education, 11*(3), 556-572. https://doi.org/10.30935/scimath/13124

ARTICLE INFO

Received: 5 Dec 2022

Accepted: 23 Mar. 2023

ABSTRACT

Technology, in particular augmented reality (AR), has the potential to greatly enhance interactive learning environments for mathematics in both classrooms and other teaching environments. The purpose of the present study was to investigate existing literature on AR in mathematics education. We selected papers from 10 databases, Scopus, Web of Science Core Collection, ERIC, IEEE Xplore Digital Library, Teacher Reference Center, SpringerLink, zbMATH Open, Taylor & Francis Online Journals, JSTOR, and MathSciNet. From these databases, 42 related studies were selected by the method of preferred reporting items for systematic reviews and meta-analysis (PRISMA2020). The results from all the papers showed positive outcomes as a result of AR implementation in mathematics education. They were also analyzed into different themes according to quantitative and qualitative criteria. The advantages and challenges of AR usage in mathematics education are also discussed in detail.

Keywords: augmented reality, systematic literature review, PRISMA2020, educational technology, mathematics education, geometry education

INTRODUCTION

The use of technological tools in various fields has grown rapidly over the last decades. Augmented reality (AR) has become a technological enabler for education, design, navigation, and medicine (Cai et al., 2019). Azuma (1997) describes AR in which three-dimensional virtual objects are integrated into the real environment in real-time. Also, AR is a crucial technology that provides remarkable tools to enhance the experience of interacting with reality (Garzón & Acevedo, 2019). The placement of virtual information within the users' immediate environment through AR improves their perception of and interaction with the actual world (Lai & Cheong, 2022).

AR is a kind of mixed reality technology involving virtual objects implemented or "augmented" in the real life. AR provides learners with new experiences by allowing them to "see" digital learning content overlaid on their existing environment. By providing personalized learning opportunities with interaction options, AR-based learning tools enable students to actively engage in the learning process and build their knowledge structures (Ibili et al., 2020).

AR is a way to see the world that is like reality, but with extra information. It can be used to see things in the physical world, or a virtual environment. The relationship between the real and virtual world has described by a figure called the reality-virtuality-mediality continuum (Milgram et al., 1994). After 27 years, this figure was revised by Skarbez et al. (2021), as shown in **Figure 1**.

They focused on multiple senses of users (i.e., hearing, sight, touch, taste, and smell,) in the revised model. They criticized that the virtual environment endpoint in the Milgram et al.'s (1994) continuum figure was ill-

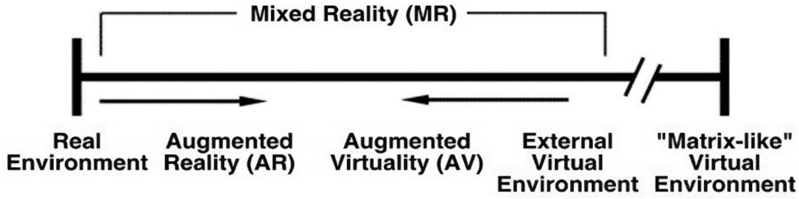

Figure 1. Revised reality-virtuality continuum by Scarbez et al. (2021)

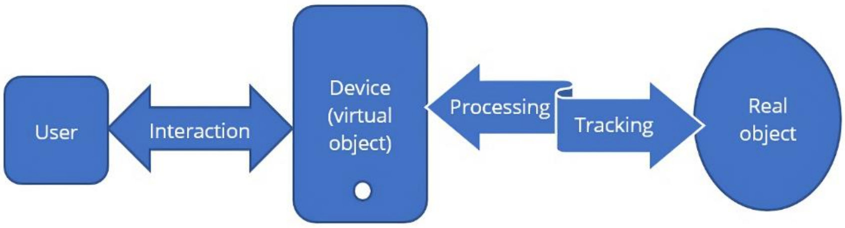

Figure 2. Augmented reality process diagram (developed by the authors)

defined. They added a matrix-like virtual environment for explaining sensory agreement as in the popular movie series Matrix. In the Matrix movies, direct brain stimulation is used to achieve sensory agreement.

Besides, by developing and spreading new mobile devices and technologies AR technology became a unique and more interactive experience. Also, AR process differs according to platforms, it contains user interaction with the device and real object's tracking processing phases. There are three main types of AR tracking technology vision-based tracking, sensor-based tracking, and hybrid tracking (Rabbi & Ullah, 2013).

As a summary of these models, it is necessary to show that AR process model includes basic elements such as user-device-real object and their interaction between them. For describing user interaction with devices and real object-virtual object relation, we present a new model that contains processing and tracking phases (**Figure 2**).

Augmented Reality in Mathematics Education

Traditionally, mathematics has been taught using paper, pencils, and chalkboards or whiteboards. However, while making progress with technology, the adoption of more advanced technology in mathematics instruction has stalled, even if educational technology has made significant advancements. Even while new technologies might not be able to solve students' problems with arithmetic problem-solving techniques, inaction will continue to halt improvements in mathematics instruction. In order to improve conceptual understanding, scaffold learning, and create chances for dialogue regarding the solution of mathematical problems used in real-life applications, educators are pushed to design novel teaching and learning methodologies (Lai & Cheong, 2022).

In mathematics education, AR has a big potential and opportunities for students to learn and interact with three-dimensional models in the real world. The usage of AR in mathematics education has increased especially in geometry and other complex concepts (Liu et al., 2019; Thamrongrat & Law, 2019). In these studies, it is reported that the use of AR has a positive effect on students' learning performance and attitude toward mathematics, especially in classes that focus on solid geometry and more abstract geometric concepts. In addition, informal settings were more effective than formal settings for the intervention.

Besides, Garzón and Acevedo (2019) investigated 64 quantitative research papers for a meta-analysis to analyze the impact of AR on students' learning gains. The researchers found that learning gains were higher when AR resources were used in teaching mathematics Furthermore, learning gains and motivation were reported as the most important benefits of AR in education. Using AR technology increases the motivation of participants not only in mathematics but also in STEAM (science, technology, engineering, arts, and mathematics). According to the researchers' observations, it occurs particularly when students' curiosity is sparked and they are challenged to create their own projects, thus making learning more enjoyable for both students (Jesionkowska et al., 2020).

Rationale for This Review

A few meta-analyses and literature reviews have been made to present AR implementation in different fields such as medicine, physics, chemistry, mathematics, geography, biology, astronomy, and history (Ibáñez & Delgado-Kloos, 2018; Saidin et al., 2015; Silva et al., 2019). However, there is a lack of systematic literature review, especially about AR usage in mathematics education. There are only a few articles that systematically reviewed the related studies on the use of AR in mathematics instruction.

This research fills the gap in mathematics education research. Especially for a more inclusive literature review this research contains 10 international research databases and 42 articles (**Appendix A**). This research has more databases and articles than previous ones. One of the previous reviews included 19 articles indexed in only Scopus database (Ahmad & Junaini, 2020). In another review, Jabar et al. (2022) reviewed five databases and a total of 20 articles. Similarly, Korkmaz and Morali (2022) investigated 20 research articles.

In this study, we systematically reviewed the existing literature in the field of AR and mathematics education. We also attempted to provide answers to the following research questions and analyzed them over time, with a focus on AR and mathematics education. This was done in order to view cumulative progress over the previous few decades.

1. How are the studies on AR usage in mathematics education distributed in terms of year of publication and authors' countries?
2. What kind of sample groups were targeted in these studies, and what were the sample sizes?
3. Which mathematics concepts or domains were selected for the studies?
4. Specifically, what types of technologies used as AR tool and what are the results for effectiveness of implementations?
5. What are the major disadvantages and challenges of AR usage in mathematics education?

METHOD

Eligibility Criteria

For examining the literature in the field of AR and mathematics education, We specified the studies, treatments, outcomes, and participants that were accepted for inclusion in the review and stated that research was excluded if it examined outcomes unrelated to students or academic instruction.

Information Sources

In the current study, we used the latest version of preferred reporting items for systematic reviews and meta-analysis (PRISMA2020) guidelines (Page et al., 2021).

Selection of Databases

The following ten databases were selected because of their significant impact on mathematics education and scientific indexing standards:

1. Scopus,
2. Web of Science (WoS) Core Collection,
3. ERIC,
4. zbMATH Open,
5. IEEEXplore Digital Library,
6. SpringerLink,
7. Taylor & Francis Online Journals,
8. Teacher Reference Center,
9. JSTOR, and
10. MathSciNet.

Table 1. Search strings

Databases	Search items
Scopus	(TITLE-ABS-KEY (augmented AND reality) AND TITLE-ABS-KEY (mathematics education) Refined by: (LIMIT-TO (SUBJAREA,"MATH") OR (SUBJAREA, "SOCI") AND (LIMIT-TO (LANGUAGE, "English")
WoS Core Collection	TOPIC: (mathematics education*AND Augmented Reality*) Refined by: WEB OF SCIENCE CATEGORIES: LANGUAGES: (English) AND (Mathematics OR Education Educational Research OR Education Special OR Education Scientific Disciplines) AND DOCUMENT TYPES: (Book Chapter OR Article OR Proceedings Paper OR Review OR Early Access)
ERIC	TI Augmented Reality AND TX mathematics education
Teacher Reference Center	TI Augmented Reality * AR* AND TX mathematics or math or math education or mathematics education
MathSciNet	TI Augmented Reality
IEEEXplore Digital Library	"Document Title": (augmented reality) AND ("Full Text & Metadata":mathematics education)
SpringerLink	Title: Augmented Reality AND math* Discipline: Education
Taylor & Francis Online Journals	[Publication Title: augmented reality] AND [All: math*]
zbMATH Open	ti: augmented reality
JSTOR	ti: Augmented Reality AND All fileds: math*
Records identified from databases	1,031

Table 2. Exclusion and inclusion criteria

Exclusion criterion (EC)	Inclusion criterion (IC)
EC1: Studies outside of field of mathematics education	IC1: Studies on mathematics education at all education levels, including mathematics as a core topic
EC2: Studies not focusing on AR & math	IC2: Studies related with AR & math in tertiary or school education
EC3: Document types: book reviews, editorials, notes, & whole books	IC3: Document types: book chapters, proceedings papers, journal articles, or reviews
EC4: Studies mentioning AR & math but not focusing on them	IC4: Studies indexed in Scopus, Web of Science Core Collection, ERIC, zbMATH Open, Teacher Reference Center, JSTOR, IEEEXplore Digital Library, SpringerLink, MathSciNet, Taylor & Francis Online Journals,
EC5: Studies not published in English	IC5: Studies published in English

AR is not only an educational topic but also a technological issue. For this reason, besides Scopus (184 articles) and WoS (273 articles) other databases were selected such as IEEEXplore Digital Library (219 articles). These high-quality scientific databases were investigated in order to establish an inclusive and wide review. Additionally, they contain a significant amount of research in the area of educational research, particularly in the field of mathematics education.

Search Strategy

The literature search was conducted on July 27, 2022. We found the related papers in the field of mathematics education research using search strings (Musarat et al., 2021) with asterisks and Boolean operators, and that contained those two elements. An excerpt of the search strategy for search terms is shown in **Table 1**.

Selection Process

For investigating the current literature in the field of AR and mathematics education, we used priority screening methods in this review. Non-English language articles were excluded. All studies done at all mathematics education levels were included in our search, and the research's publication years were not a restriction. Overall, we utilized five inclusion criteria and five exclusion criteria, as shown in **Table 2**, to determine which publications were appropriate for the evaluation.

Data Collection Process

The article selection process was implemented in three main phases: identification, screening, and inclusion (Page et al., 2021). Using the search terms from **Table 1**, 10 databases were searched for literature during the identification phase, and 1,031 records were found. For organizing references and deleting duplicate information, utilize bibliographic software. We utilized the "refine" or "limit to" functionalities of the

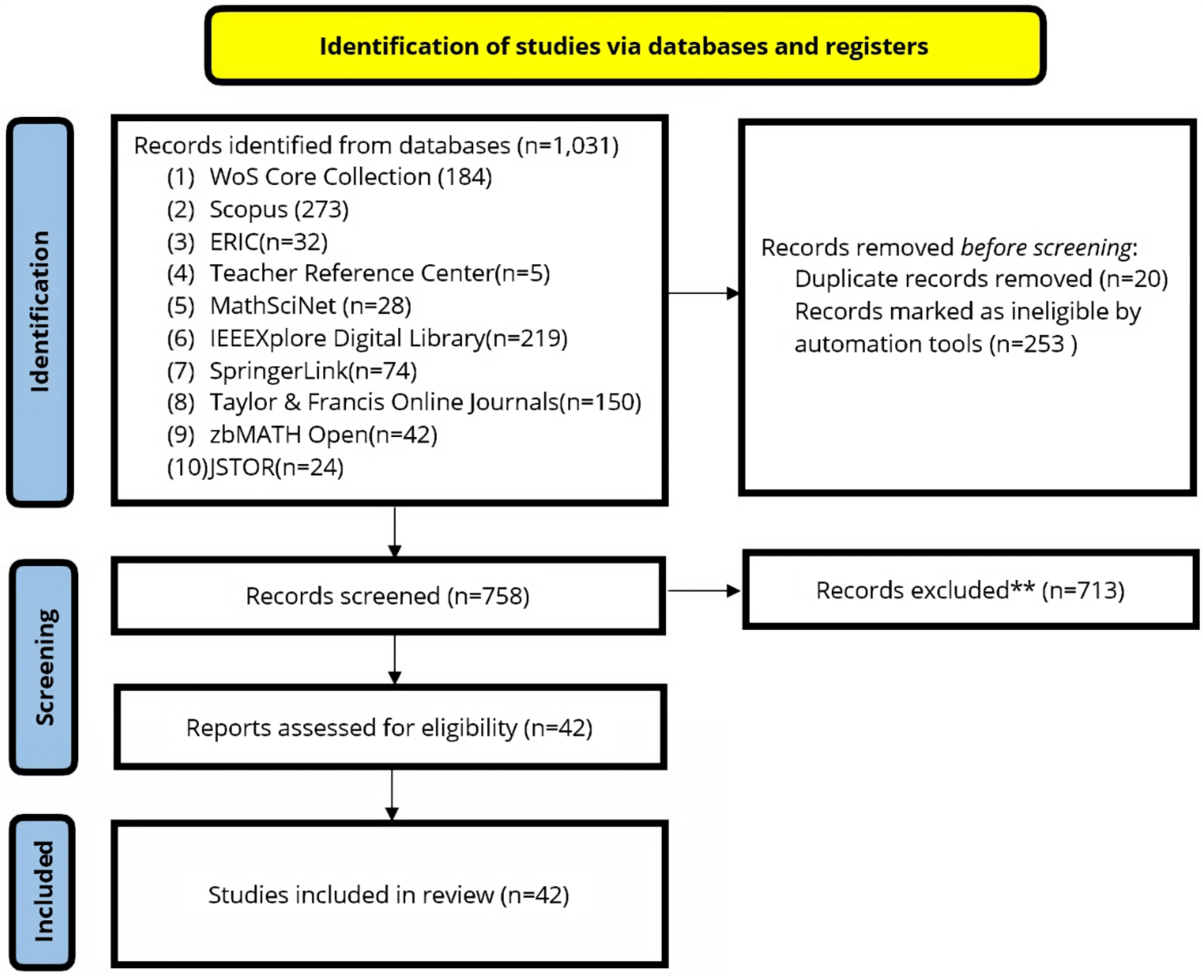

Figure 2. Flow diagram of the manuscript selection process (developed by the authors)

electronic databases to eliminate publications by choosing exclusion criteria after eliminating duplicate information. We independently reviewed the remaining 758 possibly related studies before we manually filtered them.

At the end of the screening phase, we included 42 studies in the systematic review. **Figure 2** shows the flow chart for the entire manuscript selection process. In this review, for examining the existing literature in the field of AR and mathematics education. We employed a standardized, pilot-tested form. Data was also retrieved by independent reviewers, who then had it verified by another reviewer

RESULTS AND CONCLUSIONS

In this section, the results and thus also the research questions mentioned are answered, which relate to the separate subsections.

Distribution of the Studies in Terms of Year of Publication and Authors' Countries

The findings of geographic distribution showed the contributions of researchers from various nations to the study of AR in mathematics education. Only the findings from the independent analysis based on each author's national affiliations were presented.

Figure 3 shows the distribution of the reviewed articles' authors according to the countries that were indicated in the article. The authors from the USA (n=7), Spain (n=6), Taiwan (n=4), Turkey (n=4), and China (n=3) produced the highest number of articles. Meanwhile, authors from Germany, Indonesia, Saudi Arabia, Australia, India, Malaysia, and Portugal published two articles. The remaining authors from 13 countries only published one article each.

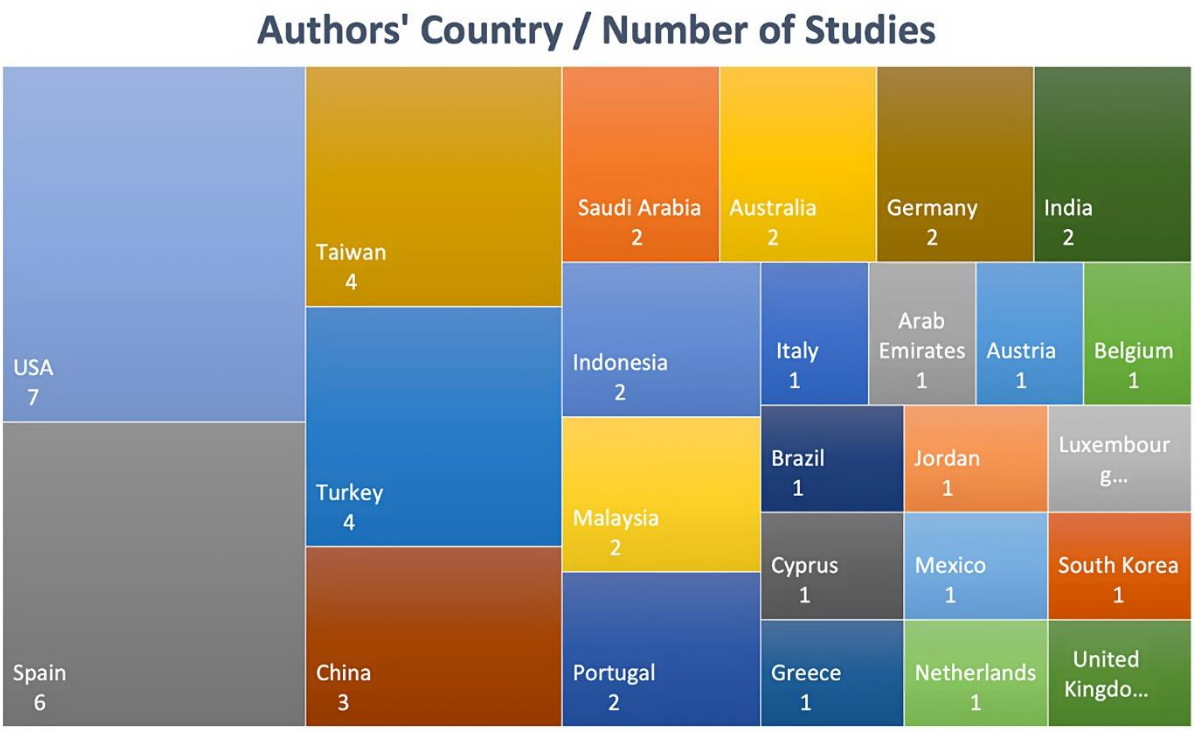

Figure 3. Authors' country affiliations and number of studies (developed by the authors)

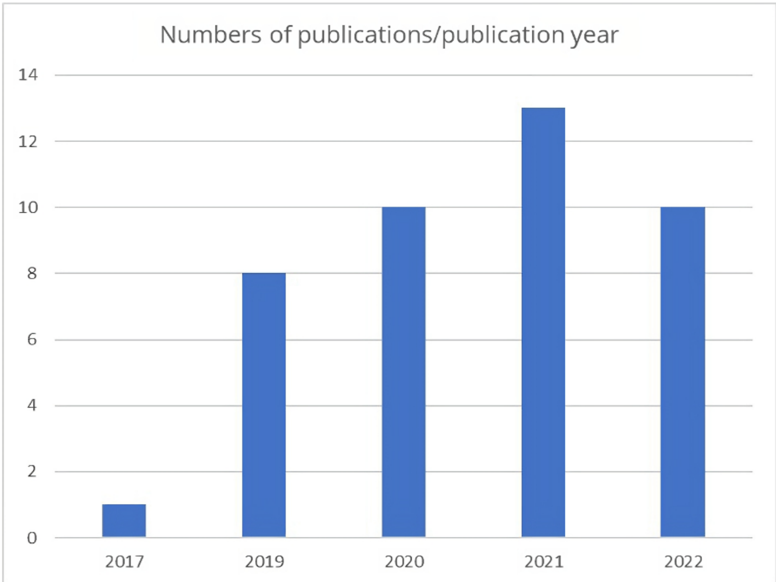

Figure 4. Trends of publication numbers according to publication years (until July 2022) (developed by the authors)

According to **Figure 3**, the authors came from European countries (Spain, Portugal, Greece, Netherlands, Italy, Austria, Belgium, United Kingdom, Turkey, Luxembourg, and Germany) and published more than half of the articles. In addition to the authors from European countries, other authors from Asian countries and the USA published the rest of the articles.

Figure 4, which is given below illustrates the trends in studies related to AR for learning mathematics between 2017 and 2022. **Figure 4** indicates that the studies on AR in mathematics education increased in recent years. The distribution of related articles in the literature in terms of publication years is shown in **Figure 4**. This may be owing to the development of commercial AR hardware and software. Especially by

Table 3. Distribution of reviewed studies according to sample group

Article code number	Participants' level of education
A1, A2, A3, & A4	Primary school students
A35	Primary school students & teachers
A5, A6, A7, A8, A11, A12, A13, A14, A15, A16, A17, A18, A19, A20, A10, A21, & A34	Secondary school students
A22, A9, A36, A37, & A38	Secondary school students + teachers
A23, A24, A25, A27, A28, & A26	Undergraduate students
A39	Undergraduates & engineering faculty teachers
A29 & A30	Pre-service teachers
A31, A32, & A33	Teachers
A40	Adults with disabilities
A41	Young adults

Table 4. Distribution of reviewed studies according to sample size

Article code number	Sample size
A24, A13, A2, A40, A41, A20, A6, & A32	01-15
A9, A29, A36, A12, A3, A15, A31, & A21	16-30
A19 & A1	31-45
A28, A30, A39, A10, A22, A18, & A37	46-60
A35, A5, & A11	61-75
A26, A27, A16, & A8	76-90
A4, A25, A17, A14, A38, A33, & A7	91+

Table 5. Distribution of reviewed studies according to mathematics concepts/domains

Article code number	F (n)	P (%)	MC/D
A21,A28,A30,A40,A6,A22,A4,A35,A39,A9,A10,A16,A34,A17,A18,A7,A23	17	40	Geometry
A31, A32,A33,A37,A38	5	12	STEM or STEAM
A1,A36,A15,A24, A2,A41,A12,A29,A20,A13,A5	11	26	Calculus, numbers or problem-solving
A11,A26, A27,A42,A3	5	12	Statistics, finance, money, & probability
A2	4	10	Algebra

Note. F: Frequency; P: Percentage; & MC/D: Mathematics concepts/domains

means of the increase in popularity of smart devices, it becomes easy to access AR tools such as smartphones and glasses.

Sample Groups and Sample Sizes of the Studies

In this study, we analyzed the characteristics of the reviewed studies' sample groups. For the categorization of the participants of the studies, the numbers and educational levels of the participants were considered.

The distribution of the examined studies by sample group is shown in **Table 3**. The majority of research appears to have been done on secondary school pupils., followed by primary school students, undergraduates, preservice teachers, and teachers. This result indicates that most of the articles reviewed focus on his K-12 level. The sample of one group was adults with disabilities and another study was about young adults. Also, some of the studies contain teachers and academic staff of universities, which are shown in **Table 3** separately.

Sample sizes of the reviewed articles were categorized to different groups. According to **Table 4**, most of the sample sizes were in the first and second categories such as between 1-15 and 16-30 participants. The following sample size categories were participant numbers 46-60 and more than 91 participants.

Focused Mathematics Concepts or Domains for the Studies

Regarding mathematics concepts or domains selected for studies, geometry (40%) most common subject in reviewed articles. The next preferred subjects were calculus, numbers, or problem-solving. Also, five articles focused on STEM or STEAM, and another five of the reviewed articles were about statistics, finance, money, and probability. The last four articles are about algebraic topics (**Table 5**).

Table 6. AR tools/technologies used in reviewed studies

Technology	n	Article code number
Unity	5	A1, A39, A37, A9, & A26,
GeoGebra AR	5	A24, A40, A10, A31, & A29
AR application	19	A35, A5, A33, A13, A6, A32, A23, A8, A7, A30, A11, A15, A17, A18, A19, A21, A28, A2, & A3
AR sandbox	1	A25
HP reveal app & iPads	5	A12, A14, A42, A41, & A27
AR-based STEM content, smartphones, & tablet	1	A2
AR prototype developed for dyscalculia learners	1	A36
AR & simulations	1	A16
Geometry AR app & tablets	1	A17
AURASMA app, checklists & booklets as guidelines, calculator, & iPads	1	A20
AR mobile math trails app	1	A22
Geo+	1	A4

Table 7. The conclusions and effectiveness of the reviewed studies

Conclusions of reviewed studies	Article code number
Increase in engagement	A1, A40, A37, A6, A10, A22, & A25
Increase in enjoyment	A1, A40, A37, A4, A8, & A15
Visualization skills improved	A24 & A18
Found it interesting	A24, A37, A39, A7, A32, A13, & A42
Easy to understand	A2
Easy to use	A39, A34, A35, & A7
Improve understanding	A24, A10, & A20
cooperation and teamwork with others	A37, A14, A35, & A23
interdisciplinary: Different fields' combination	A35, A31, & A17
Increase in academic performance & students' learning gain	A5, A30, A21, A29, A4, A9, A33, A16, & A27
Mathematical modelling skills increased	A5 & A22
Improving spatial ability	A6 & A23
Increase motivation	A33, A26, A31, A3, A22, A39, A7, & A9
Retention & helps recalling mathematical formulas	A39, A9, & A28
Increased problem solving skills	A9, A41 & A2
Effective instruction to students with disabilities	A12, A36, A20, & A3
Positive effects on perception & attitudes towards AR	A34, A11, A19, & A10

Types of Technologies Used as Augmented Reality Tool and Their Effectiveness

AR applications were used in most of the reviewed articles. The second most-used AR development tools are HP reveal, unity, and GeoGebra to enhance mathematics teaching and learning (**Table 6**).

The other remaining development tools and technologies are AR sandbox, the development tools, AR-based STEM content, smartphones, tablet, AR prototype developed for dyscalculia learners, AR and simulations geometry AR app, tablets, AURASMA app, checklists and booklets as guidelines, calculator, iPad, AR mobile math trails app, and Geo+ mentioned in each one of the remaining articles (**Table 6**).

According to the conclusions of the reviewed studies the most dominant effects were the increase in academic performance and students' learning gains (A5, A30, A21, A29, A4, A9, A33, A16, A27) (**Table 7**). AR-based learning could effectively enhance academic achievement. From the findings of the studies, it can be concluded that students who were exposed to a learning methodology with AR obtained better results in the level of learning achievement.

Participants of some reviewed articles found that AR is interesting (A24, A37, A39, A7, A32, A13, and A42), easy to understand (A2), and easy to use (A39, A34, A35, and A7). Another significant conclusion is that AR helps to increase the motivation of participants (A33, A26, A31, A3, A22, A39, A7, and A9). Especially the younger participants felt more motivated in a very positive and motivating way (A26 and A31). AR delivers effective instruction to students with disabilities (A12, A36, A20, and A3). AR activities were not only effective as a learning tool, but they were also motivating for students with special educational needs (A3). Some of the studies showed that AR increases student independence and supports individual learning (A12).

Also, AR has provided students to learn individually and allowed students to manage their own learning process. Students were in an active learning process with tasks and choosing their own way to examine the virtual objects (A6 and A12). According to the results of the studies coded A23 and A6, AR applications increase the spatial intelligence/spatial visualization abilities of students. In addition to spatial abilities AR is effective in the development of each of the visual thinking skills (A24 and A18) These skills have been titled as, scientific deduction skill, visual reading skill, the skill of analyzing, interpreting visual discrimination skill and the visual shape According to conclusions of the studies AR makes understanding easier for students (A24, A10, and A20). AR improve understanding of concepts and enables an investigative environment, not the computers' mouse move, the person, the space moves within AR environment (A24). According to conclusions of A33, it is emphasized that AR provides concrete examples for mathematical concepts.

Some of the studies (Chen, 2019; Jesionkowska et al., 2020; Fernández-Enríquez & Delgado-Martín, 2020; Schutera et al., 2021) pointed out that AR is beneficial for cooperation and teamwork by improving social and communication skills, development of critical thinking to make logical decisions and project management with others. Also Fernández-Enríquez and Delgado-Martín (2020) points out that AR apps can be used on any device for producing content interdisciplinary: different fields' combination (computer science, 3D technology, videogame programming, AR, and application creation) In A31, researchers concluded that the results of the STEAM integrated approach professional development with in-service teachers on outdoor trails were quite impressive.

In experimental studies Alqarni and Alzahrani (2022) and Cahyono et al.'s (2020) results indicated that the mean scores of the experimental group with AR are statistically higher than control groups. There was a significant difference ($p<0.001$) between the students' mathematical modeling abilities before and after the intervention. By using AR the students' deduction, mathematical proof and modeling skills increased (A5). Some of the studies also focused on retention (A39, A9, and A28). According to the results of AR provides an improved remembering and retention rate. Especially in terms of retention for experimental studies, AR has a significant major impact on memory retention, there is also a significant major difference between groups (A28). According to the results of the studies A9, A41, and A2 by following AR course, all participants showed significant development in problem-solving ability. Students could develop problem-solving skills on word problems, financial problems, and multistep problems. Perceptions and attitudes have a strong effect on the teachers' intentions of continuous use (A34, A11, A19, and A10). AR can help when teachers perceived the ease of use of AR system. It is found in A10 that perceived of usefulness is the strongest factor in predicting students' behavior in the use of GeoGebra AR ones should be explained in clear terms at first mention. Metric equivalents for all non-metric units should be provided.

Disadvantages and Challenges of Augmented Reality in Mathematics Education?

While articles associated with AR in mathematics education emphasized the advantages of its application, there are several obstacles encountered in implementing the technology. The most commonly identified challenges were technical problems with the usage of AR. Some of the technical problems are stated in studies as hardware requirements to support AR, device memory and CPU usage of AR applications, lack of quality internet connection, prolonged use of the application slows down and warms up the device, tracking time varies according to the Internet connection quality (Chen, 2019; Fernández-Enríquez & Delgado-Martín, 2020; Fidan & Tuncel, 2019; Hernández Moreno et al., 2021; Marques & Pombo, 2021a). Also, there are other problems reported such as reading tiredness on small screens of smartphones (Hsieh & Chen, 2019; Gargrish et al., 2022)

In addition to technical problems, there are several challenges to pedagogical issues. According to the results of the studies it is found that difficulty of training teachers and its required time and the lack of teachers and students' technological competencies are major barriers to the implementation of AR (Fernández-Enríquez & Delgado-Martín, 2020; Marques & Pombo, 2021a). One of the other pedagogical problems is ineffective classroom integration to learner differences (Jesionkowska et al., 2020). Also, it is stated that teachers' lack of motivation to use new technologies makes it difficult to use AR in mathematics classrooms (Marques & Pombo, 2021b).

Another problem is the learning environment. Because it is found that there were some challenges for students during mathematics lessons because of paying too much attention to virtual information (Jesionkowska et al., 2020; Marques & Pombo, 2021b).

There are other challenges such as a lack of materials apps and lesson scenarios and a lack of suitable digital sources (Jesionkowska et al., 2020; Marques & Pombo, 2021b). Also, there are some problems with human-computer interaction such as less face-to-face interaction between people and dehumanizing the teaching-learning process (Fernández-Enríquez & Delgado-Martín, 2020). Moreover, usability difficulties are also another challenge for implementing AR in mathematics education (Jesionkowska et al., 2020). Also, it is stated that it is difficult to implement AR in classrooms due to the economic costs of technical devices (Fernández-Enríquez & Delgado-Martín, 2020). On the contrary, other researchers claimed that the technological developments of portable gadgets and lower prices of these devices may reduce these threats in the upcoming years (Sirakaya & Alsancak Sirakaya, 2020).

DISSCUSSION

The most frequently mentioned benefit of AR systems in education is still learning benefits, followed by motivation. It is significant to note that every new study continues to document several benefits that enhance not just students' academic performance but also numerous other personality qualities including autonomy, creativity, and teamwork (Garzón & Acevedo, 2019; Silva et.al., 2019). Additionally, the fact that AR systems improve kids' enthusiasm and academic performance may eventually lower the expenses of grade repetition, early school or college dropout, as well as the social issues these occurrences may bring about. Also, the most frequently cited advantages of AR are that they encourage academic success, aids with visualization, and support student-centered learning (Ajit et al., 2021). It is possible to draw the conclusion that as the usage of mobile devices grows, particularly in developing nations, so will the use of AR technology. The use of AR in mathematics education helps the teaching and learning process, according to research findings. It should be remembered, nevertheless, that the novelty effect can also play a role (Garzón & Acevedo, 2019).

To create quality educational materials, the process of developing AR apps should involve engineers (to design code), educators (as theme experts), and other professionals (Cuendet et al., 2013). Similarly to this, a diverse team should make sure that AR apps have capabilities that allow individuals with any kind of disadvantaged people to connect with them, considering the unique preferences and requirements of teachers and students (Garzón & Acevedo, 2019).

The benefits of employing AR appear obvious; therefore, it is also crucial to constantly grow and come up with new approaches to gain. As a result, for academic courses that need students to master abstract information and abilities, we could fully utilize AR education's concrete, interactive environment to turn lessons into concrete learning content, and help students to better comprehend such subjects going ahead.

Furthermore, the substantial effectiveness of utilizing AR to learn over longer periods of time indicates that students require a period of adaptation to AR learning method. Thus, in order to achieve a satisfying AR application effect in mathematics education, a long-term teaching design must be developed, followed by the implementation and integration of AR into teaching.

Although AR seems to have many educational advantages, there are still obstacles that this technology must overcome, such as complexity, technical issues, and even teacher resistance. The integration process of AR in mathematics education could be challenging because of technical and pedagogical issues. Advances in mobile technology may be able to help solve these technical issues in the upcoming years. Although there are other difficulties including instructor attitudes toward AR and the requirement for development times for material. The provision of the knowledge and skills required for the successful application of AR in mathematics education is vital, as is overcoming teacher opposition. In ways to help instructors and offer professional development for utilizing AR in mathematics education, further studies are necessary. It is possible to create educational AR resources and AR authoring tools that teachers may use for free. Teachers may take steps to guarantee that AR learning is implemented properly, ideas as integrating physical teaching instruments with AR learning systems to allow students to experience connecting pupils virtual learning with their physical learning by using both virtual and offering hands-on training opportunities (Li et al., 2019).

It is possible to create educational AR resources and AR authoring tools that teachers may use for free. To address these issues, both application developers and researchers might carry out more studies. Future research should explore other difficulties with AR that have been noted in the literature. In earlier research, secondary education teachers and students were preferred as sample groups. According to the evaluation of AR and mathematics education research, secondary school kids are the perfect sample groups, therefore the promise of AR might be expanded beyond only emphasizing student performance and learning outcomes.

Limitations

It is important to mention several limitations of this study. First, just forty-two articles were investigated throughout the review procedure. The journals included in the selected ten databases are the only ones whose papers were examined for this study. However, you may also utilize other databases. The selected databases were searched with a limited number of keywords. For a more thorough understanding of the impact of AR application on K-12 education, future studies should analyze additional factors. Various grade levels and subjects have different benefits and drawbacks that should also be researched in the future.

With this literature study, it is hoped to provide stakeholders with a roadmap for ensuring that AR systems are appropriately included in educational settings and demonstrating AR's state in mathematics education. In order to maximize the benefits of this technology, it is crucial that governmental organizations, businesses, and educational institutions invest more budget in initiatives aimed at creating AR systems. Software developers should work to resolve the technical issues with AR pedagogical tools to make it easier for users to use them, especially those with little technological expertise and those with disabilities. Finally, researchers should carry out more studies to show how effective AR is in mathematics education.

Author contributions: All authors were involved in concept, design, collection of data, interpretation, writing, and critically revising the article. All authors approved the final version of the article.

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

Ethics declaration: Authors declared that only previously published scientific papers were used to conduct this systematic review. No additional personal data was collected; therefore, this work was not reviewed by an ethics committee.

Declaration of interest: Authors declare no competing interest.

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

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APPENDIX A

Table A1. List of articles used in the systematic review

No	Article
A1	Rebollo, C., Remolar, I., Rossano, V., & Lanzilotti, R. (2022). Multimedia augmented reality game for learning math. *Multimedia Tools and Applications, 81*(11), 14851-14868. https://doi.org/10.1007/s11042-021-10821-3
A2	Wu, C.-L. (2022). Using video modeling with augmented reality to teach students with developmental disabilities to solve mathematical word problems. *Journal of Developmental and Physical Disabilities*. https://doi.org/10.1007/s10882-022-09862-9
A3	Cascales-Martínez, A., Martínez Segura, M.-J., López, D., & Contero, M. (2016). Using an augmented reality enhanced tabletop system to promote learning of mathematics: A case study with students with special educational needs. *EURASIA Journal of Mathematics, Science and Technology Education, 13*, 355-380. https://doi.org/10.12973/eurasia.2017.00621a
A4	Rossano, V., Lanzilotti, R., Cazzolla, A., & Roselli, T. (2020). Augmented reality to support geometry learning. *IEEE Access, 8*, 107772-107780. https://doi.org/10.1109/ACCESS.2020.3000990
A5	Alqarni A. S., & Alzahrani R. R. The impact of augmented reality on developing students' mathematical thinking skills. *IJCSNS International Journal of Computer Science and Network Security*, 22(3), 553-556.
A6	Ozcakir, B., & Cakiroglu, E. (2022). Fostering spatial abilities of middle school students through augmented reality: Spatial strategies. *Education and Information Technologies, 27*(3), 2977-3010. https://doi.org/10.1007/s10639-021-10729-3
A7	Ozcakir, B., & Ozdemir, D. (2022). Reliability and validity study of an augmented reality supported mathematics education attitude scale. *International Journal of Human-Computer Interaction, 38*(17), 1638-1650. https://doi.org/10.1080/10447318.2022.2092955
A8	Li, S., Shen, Y., Jiao, X., & Cai, S. (2022). Using augmented reality to enhance students' representational fluency: The case of linear functions. *Mathematics, 10*(10), 1718. https://doi.org/10.3390/math10101718
A9	Gargrish, S., Mantri, A., & Kaur, D. P. (2022). Evaluation of memory retention among students using augmented reality based geometry learning assistant. *Education and Information Technologies, 27*(9), 12891-12912. https://doi.org/10.1007/s10639-022-11147-9
A10	Mailizar, M., & Johar, R. (2021). Examining students' intention to use augmented reality in a project-based geometry learning environment. *International Journal of Instruction, 14*, 773-790. https://doi.org/10.29333/iji.2021.14243a
A11	Cai, S., Liu, E., Shen, Y., Liu, L., Li, S., & Shen, Y. (2020). Probability learning in mathematics using augmented reality: impact on student's learning gains and attitudes. *Interactive Learning Environments, 28*, 560-573. https://doi.org/10.1080/10494820.2019.1696839
A12	Kellems, R. O., Cacciatore, G., Hansen, B. D., Sabey, C. V., Bussey, H. C., & Morris, J. R. (2021). Effectiveness of video prompting delivered via augmented reality for teaching transition-related math skills to adults with intellectual disabilities. *Journal of Special Education Technology, 36*(4), 258-270. https://doi.org/10.1177/0162643420916879
A13	Morris, J., Hughes, E., Stocker, J., & Davis, E. (2021). Using video modeling, explicit instruction, and augmented reality to teach mathematics to students with disabilities. *Learning Disability Quarterly, 45*, 073194872110404. https://doi.org/10.1177/07319487211040470
A14	Chen, Y.-C. (2019). Effect of mobile augmented reality on learning performance, motivation, and math anxiety in a math course. *Journal of Educational Computing Research, 57*(7), 1695-1722. https://doi.org/10.1177/0735633119854036
A15	Cheng, Y.-W., Wang, Y., Cheng, I. L., & Chen, N.-S. (2019). An in-depth analysis of the interaction transitions in a collaborative augmented reality-based mathematic game. *Interactive Learning Environments, 27*(5-6), 782-796. https://doi.org/10.1080/10494820.2019.1610448
A16	Aldalalah, O. M., Ababneh, Z., Bawaneh, A., & Alzubi, W. (2019). Effect of augmented reality and simulation on the achievement of mathematics and visual thinking among students. *International Journal of Emerging Technologies in Learning, 14*(18), 164-185. https://doi.org/10.3991/ijet.v14i18.10748
A17	Sánchez, S., López-Belmonte, J., Moreno Guerrero, A., & Cabrera, A. (2021). Effectiveness of flipped learning and augmented reality in the new educational normality of the COVID-19 era. *Texto Livre Linguagem e Tecnologia* [*Free Text Language and Technology*], *14*, 1-16. https://doi.org/10.35699/1983-3652.2021.34260
A18	Bani Ahmad, F. (2021). The effect of augmented reality in improving visual thinking in mathematics of 10th-grade students in Jordan. *International Journal of Advanced Computer Science and Applications*, *12*(5), 352-360. https://doi.org/10.14569/IJACSA.2021.0120543
A19	Saundarajan, K., Osman, S., Kumar, J. A., Daud, M. F., Abu, M. S., & Pairan, M. R. (2020). Learning algebra using augmented reality: A preliminary investigation on the application of photo math for lower secondary education. *International Journal of Emerging Technologies in Learning, 15*(16), 123-133. https://doi.org/10.3991/ijet.v15i16.10540
A20	Kellems, R. O., Eichelberger, C., Cacciatore, G., Jensen, M., Frazier, B., Simons, K., & Zaru, M. (2020). Using video-based instruction via augmented reality to teach mathematics to middle school students with learning disabilities. *Journal of Learning Disabilities, 53*(4), 277-291. https://doi.org/10.1177/0022219420906452

Table A1 (Continued). List of articles used in the systematic review

No	Article
A21	Flores-Bascuñana, M., Diago, P. D., Villena-Taranilla, R., & Yáñez, D. F. (2020). On augmented reality for the learning of 3D-geometric contents: A preliminary exploratory study with 6-grade primary students. *Education Sciences, 10*(1), 4. https://doi.org/10.3390/educsci10010004
A22	Cahyono, A. N., Leonardus Sukestiyarno, Y., Asikin, M., Miftahudin, M., Kafi Ahsan, M., & Ludwig, M. (2020). Learning mathematical modelling with augmented reality mobile math trails program: How can it work? *Journal on Mathematics Education, 11*, 181-192. https://doi.org/10.22342/jme.11.2.10729.181-192
A23	Schutera, S., Schnierle, M., Wu, M., Pertzel, T., Seybold, J., Bauer, P., Teutscher, D., Raedle, M., Heß-Mohr, N., Röck, S., & Krause, M. J. (2021). On the potential of augmented reality for mathematics teaching with the application cleARmaths. *Education Sciences, 11*(8), 368. https://doi.org/10.3390/educsci11080368
A24	Monteiro Paulo, R., Pereira, A. L., & Pavanelo, E. (2021). The constitution of mathematical knowledge with augmented reality. The Mathematics Enthusiast, 18(3), 11. https://doi.org/10.54870/1551-3440.1539
A25	Bos, R., Doorman, M., Drijvers, P., & Shvarts, A. (2021). Embodied design using augmented reality: The case of the gradient. *Teaching Mathematics and its Applications: An International Journal of the IMA, 41*(2), 125-141. https://doi.org/10.1093/teamat/hrab011
A26	Hernández Moreno, L. A., López Solórzano, J. G., Tovar Morales, M. T., Vergara Villegas, O. O., & Cruz Sánchez, V. G. (2021). Effects of using mobile augmented reality for simple interest computation in a financial mathematics course. *PeerJ Computer Science, 7*, e618. https://doi.org/10.7717/peerj-cs.618
A27	Kazanidis, I., & Pellas, N. (2019). Developing and assessing augmented reality applications for mathematics with trainee instructional media designers: An exploratory study on user experience. *Journal of Universal Computer Science, 25*, 489-514. https://doi.org/10.3217/jucs-025-05-0489
A28	Gargrish, S., Kaur, D. P., Mantri, A., Singh, G., & Sharma, B. (2021). Measuring effectiveness of augmented reality-based geometry learning assistant on memory retention abilities of the students in 3D geometry. *Computer Applications in Engineering Education, 29*(6), 1811-1824. https://doi.org/10.1002/cae.22424
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