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Augmented Reality in Mathematics Education: A Systematic Review

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The aim of this study is to explore the application of augmented reality technology in mathematics education. To accomplish this, papers related to Augmented Reality (AR) and mathematics, indexed in the Web of Science, ERIC, and SCOPUS databases from January 2010 to June 2024, were analysed. The review process identified a total of 645 items: 415 from the Web of Science, 113 from the ERIC, and 117 from the SCOPUS. Following the application of our relevance criteria, unrelated articles were removed, resulting in a final selection of 96 articles for examination in this study. The findings indicate a year-on-year increase in publications, reflecting the growing prominence of AR in the field. However, there seems to be a recent trend of stabilization, which may be temporary. Also, most of these studies were conducted with middle school or university students. Based on the reviewed papers, there is a trend that AR applications are generally prepared for the geometry and measurement topics of mathematics courses. Although there are some limitations such as insufficient technical infrastructure, operating system incompatibility, and the shift of attention to software rather than content, AR can positively affect students' attitudes and interest towards mathematics, motivation, spatial ability, creative thinking skills, high-level strategy use, and self-efficacy.

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Introduction

The integration of technology into educational contexts offers significant opportunities to accommodate various teaching and learning styles. Technology-enhanced lessons can foster more innovative approaches to both teaching and learning (Shapley et al., 2011). Utilizing technology in educational settings allows for the simulation of concepts, interaction with experts in the field, enhancement of existing informational resources, and the introduction of real-world problems into the classroom environment (Shapley et al., 2011). Additionally, it has been shown to improve student learning and engagement (Bacca et al., 2014). Recent studies further support these claims, highlighting that integrating information technology in education can enhance teaching methods, enrich learning materials, and improve teaching effectiveness and student learning quality (Arhin et al., 2024; Hsieh & Maritz, 2023; Radovan & Radovan, 2023). Augmented Reality has emerged as a prominent technology used in educational settings in recent years.

AR is a three-dimensional technology that combines the physical world with digital elements in real-time. This synthesis enriches the real-world setting by embedding digital data (Ibáñez & Delgado-Kloos, 2018). AR integrates computer-generated information or virtual objects into reality, where the reality can be an object or geographic place (Berryman, 2012). These digital elements and/or virtual objects subsequently seem to occupy the same space as physical objects in the real world (Azuma et al., 2001). According to Azuma (1997), AR systems are characterized by three distinct features: i) the integration of real and virtual objects within a physical environment, ii) interaction in real-time, and iii) the alignment of virtual and real objects in a three-dimensional space. These systems project digital artifacts into physical environments, aiding users in visualizing concepts and ideas (Wu et al., 2013). These virtual artifacts can be projected via technological devices such as tablet personal computers, smart-glasses, or other transparent surfaces such as windshields (Riegler et al., 2019). AR helps to enrich the sensory experience of users by providing real-time interaction with digital content (Azuma, 1997). AR experiences aim to enhance real-world settings through real-time interaction and precise three-dimensional alignment of virtual and physical objects (Madeira et al., 2022).

The utilization of AR technologies in educational environments has seen a significant rise in popularity over the past decade, garnering recognition from a growing number of researchers (Mystakidis et al., 2021). AR possesses the potential to influence education by bridging the gap between the real and virtual worlds, thereby providing novel approaches to learning and teaching (Martin et al., 2011; Wu et al., 2013). Recent research by Algerafi et al. (2023) provides a thorough evaluation of the educational uses of AR and VR, highlighting their effects on student motivation, learning outcomes, and engagement across different educational fields, thereby reinforcing these assertions. AR is purported to enhance learning across various educational fields, including the development of spatial abilities, mechanical skills, and language education (Diegmann et al., 2015). AR facilitates seamless interaction between virtual and real environments (Azuma et al., 2011), providing an innovative approach to learning 3D shapes that surpasses traditional methods involving tangible objects (Cuendet et al., 2013). It is readily accessible to students through the mobile devices they use in their daily lives (Lee, 2019). Cerqueira and Kirner (2012) identify visualization and interaction as two fundamental features of AR. It allows for detailed visualization and animation of abstract concepts such as chemical bonds in a way that can decrease the misconceptions that students may develop due to their inability to visualize. Moreover, AR provides micro and macro visualization of the concepts and objects that students cannot otherwise observe through the naked eye. It allows students to interact with visualized objects from different viewing angles and in different ways so that they can better understand the subject (Cerqueira & Kirner, 2012). AR allows for reality enrichment; not only with images, but also with audio-video streaming technology, which helps students to observe computer-generated information with real-world objects from a different angle and in greater detail (Martín-Gutiérrez et al., 2015). In addition, AR is supposed suitable for students of all ages because its well-designed systems do not require complex skills to use. For example, in a well-designed system, enriched reality can be observed via pointing a device's camera to certain targets dedicated for AR. Moreover, most AR systems are not dependent on specific devices and can be operated using generally low-cost mobile devices such as tablets, PCs, or smartphones. (Mystakidis et al., 2021). AR can positively influence students' emotions, thereby enhancing their attention, motivation, and interest in their educational activities (Chu et al., 2019; Salar et al., 2020; Singh et al., 2019). Research has demonstrated that it positively impacts learners' achievement and satisfaction (Lin & Chen, 2020; Thees et al., 2020), while also enhancing their knowledge and conceptual understanding. Additionally, it aids in the development of essential skills, including communication, problem-solving, and collaboration (Ke & Hsu, 2015). AR technologies can be applied not only to one sense, sight, but also to smell, touch, and hearing (Azuma et al., 2001).

A growing body of research has explored the use of AR in various educational fields, examining aspects such as its applications, objectives, challenges, benefits, effectiveness, and limitations. Despite this, there have been few systematic literature reviews in recent years focusing on these aspects of AR within the educational domain, particularly in mathematics education. Consequently, this study aims to investigate the current status of AR in mathematics education by analysing several factors, including research design, participants, learning areas, countries, benefits, and purposes. The investigation of these factors is aimed at helping researchers and educators to obtain an overview of the challenges, trends, and opportunities of AR usage for further research. Also, a systematic review aimed at identifying effective practices will provide a comprehensive analysis of the existing literature and elucidate the pedagogical impacts of AR use in education. Such a review will serve as a guide for educators and policymakers, offering valuable insights for future research. By determining which strategies and practices are most effective in AR-based mathematics education, a systematic review will contribute to maximizing the potential of this technology in education, thereby providing the necessary knowledge base. For this purpose, the research questions guiding the study are identified as follows;

(1) What are the contemporary trends in scientific studies on the use of augmented reality (AR) technology in mathematics education?
(2) What are the educational gains reported in scientific studies on the use of augmented reality (AR) technology in mathematics education?

To address these research questions, this study will investigate the foundational research methodologies, identify the countries where the research has been undertaken, ascertain the mathematical learning areas investigated, and analyse the temporal distribution of the studies. Furthermore, comprehensive insights will be provided regarding: the specific topics within mathematics education where AR is predominantly employed, the areas where AR has demonstrated higher efficacy, and the primary objectives behind the utilization of AR software or tools.

As previously mentioned, due to advancements in technological tools and settings, there's a growing trend in AR research and applications. Given the vast diversity and applications of AR, there is a need for concise overviews. In the next section, comprehensive insights that underpin the exploration of the research question and facilitate a clearer comprehension of this investigation will be presented. This will encompass the evolution, distinct characteristics, and definition of AR, along with its application in both general and mathematics education contexts.

Background and Related Context

Augmented Reality

Although AR is a comparatively novel and developing technology, the literature provides a variety of AR definitions. For instance, Klopfer and Squire (2008) defined AR as "a situation in which a real-world context is dynamically overlaid with coherent location or context-sensitive virtual information" (p. 205); whereas Milgram et al. (1995) declared AR to be a "form of virtual reality where the participant's head-mounted display is transparent, allowing a clear view of the real world" (p. 283). Similarly, Cuendet et al. (2013) pointed out that "AR refers to technologies that project digital materials onto real-world objects" (p. 557). El Sayed et al. (2011) suggest that AR aids in supplementing real-life situations with missing information by integrating virtual objects into a real-world environment. According to Chen and Tsai (2012), AR provides interaction with 2D or 3D information embedded in real scenes. AR enhances the user's understanding and experience by merging digital information with the real world. Essentially, it overlays the physical environment with useful digital content (Berryman, 2012).

Although AR technologies are developed and programmed based on the techniques used in virtual reality (VR) (Lee et al., 2017), there is a clear distinction that can be drawn between VR and AR. Milgram and Kishino (1994) prepared a reality-virtual continuum diagram which demonstrates the differences between AR, VR, and augmented virtuality (AV) (see Figure 1).

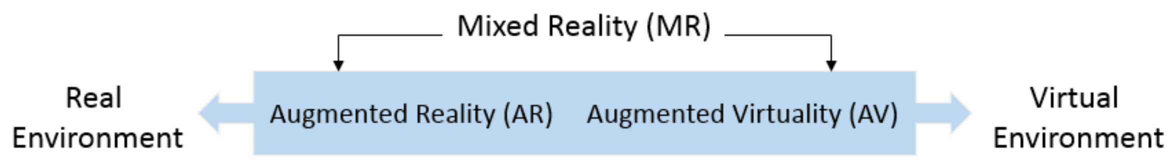

Figure 1. Reality - Virtuality Continuum

In the one-dimensional reality-virtuality continuum, AR is positioned close to the physical environment, whilst VR is situated at the opposite end, within the synthetic virtual environment. In AV, "the primary world being experienced is in fact [...] predominantly 'virtual'" (Milgram & Kishino, 1994, p. 1326) and the environment is augmented with real-world information; whereas, in the VR environment, "the participant-observer is immersed in a completely synthetic world" (Milgram et al., 1995, p. 283). According to Wojciechowski and Cellary (2013), AR is an extension of VR and has more advantages over VR. It is, however, significantly different from VR since, unlike VR in which everything is a simulation of reality, its primary component is physical reality (Berryman, 2012). In other words, AR does not completely replace reality; instead, it enhances reality (Azuma, 1997).

AR technologies have attracted the attention of more users due to the proliferation of smartphones (Berryman, 2012). The power of mobile devices and personal computers has been enhanced, leading to an increase in the development and application of AR technologies in a variety of fields such as entertainment, fashion, medicine, marketing, gaming, sightseeing, as well as in education (Berryman, 2012; Johnson et al., 2010).

AR usage in educational settings

Cuendet et al. (2013) suggested that AR systems can greatly enhance the learning process by allowing learners to interact with the physical environment in ways that would otherwise be impossible. Essentially, AR systems create unique situations that cannot be replicated solely within a physical or digital environment. Over the past decade, AR has become a significant focus of educational research. The literature includes numerous systematic reviews that explore the application of AR in education. These reviews generally assess the use of AR technology in educational settings, highlighting its positive effects on teaching and learning, as well as its limitations and challenges.

For example, Sırakaya and Alsancak Sırakaya's (2018) systematic review on augmented reality (AR) in education presents valuable findings for future research. The study reveals that the use of AR in education has significantly increased over the years, primarily in the fields of science, engineering, and medicine. Most of the studies were conducted on undergraduate students, predominantly using quantitative methods. The most commonly used type of AR is marker-based AR, and mobile devices are widely utilized. Findings of the study indicate that AR in education holds significant potential for future research and applications, highlighting the need for further exploration in this field. Another systematic review conducted by Sırakaya and Alsancak Sırakaya (2022) examined research on the use of augmented reality (AR) to support Science, Technology, Engineering, and Mathematics (STEM) education. The study analysed 42 articles indexed in the SSCI database. It was found that studies in this field have become more significant and intensive in recent years, typically utilizing marker-based AR applications. The research primarily involved K-12 students as participants and predominantly employed quantitative methods. The advantages of AR in STEM education were summarized into four sub-categories: "contribution to learners," "educational outcomes," "interaction," and "other advantages." However, challenges such as teacher resistance and technical problems were also identified.

Additionally, Bacca et al. (2014) reviewed 32 different studies that are published in six indexed journals from 2003 to 2013. In their systematic review, they provide information about the advantages, effectiveness and features of AR in education context. They also addressed the challenges and limitations of AR in education. Firstly, the researchers found out that the number of AR studies increased from 2009 to 2013. Additionally, they found that the major fields in which AR was applied were science, social sciences and arts. The studies were generally carried out with medium-sized samples, ranging from 30 to 200 participants. Furthermore, mixed research methods were also applied. Interviews, questionnaires, and surveys were found to be the most popular data collection tools used in the AR studies. They also found that although usability problems were main limitations of AR, the learning gains, collaboration, motivation and interaction were the main advantages of AR. AR technologies were shown to be effective in enhancing motivation to learning, improving academic performance, developing a positive attitude, and significantly increasing student engagement in educational settings.

Similarly, in a meta-analysis by Radu (2014), 26 publications were analysed and the positive and negative effects of AR on the learning process of the students were examined. According to Radu (2014), Although it was shown to cause usability problems and increased cognitive load, AR is beneficial to enhancing the motivation and spatial abilities of students. Additionally, the author states that by the help of AR students increase their academic performance in physics. Furthermore, AR facilitates collaboration with peers. Akçayır and Akçayır (2017) conducted a systematic review to investigate the use of AR in the K-12 setting and analysed 68 research articles published between 2007 and 2015. They focused on learner type, publication year, and the technologies used in AR, and listed the advantages and challenges of its usage. According to the researchers, the number of AR studies increased over the time period examined, with mobile devices being the most preferred delivery technology. The enhancement of motivation, enjoyment, and achievement were listed as advantages, whereas usability issues such as difficulty of usage and technical problems like recognition of trigger or execution time were identified as the main challenges.

Gof et al. (2018) analysed the implementation of AR within informal science education settings (e.g., aquariums and museums), and found that the use of exhibit-based AR can enhance the engagement, collaboration, and interest of students in the topic. Garzón et al. (2019) presented a meta-review of 61 studies published between 2011 and 2018 which investigated the learning outcomes of AR-based instruction. They found that the number of AR studies showed an increasing trend and that primary education was the most common target group. They also revealed that the natural sciences, mathematics, and statistics were the major fields in which the AR studies had been applied, and it was seen that AR technologies had a medium effect on learning effectiveness, and considerably enhanced motivation and learning gains. Likewise, Herpich et al. (2019) examined the educational theories employed in the design and evaluation of AR for educational purposes, identifying inquiry-based learning, cognitive learning theory, and collaborative learning as the most frequently applied. Similarly, Arici et al. (2019) explored the utilization of AR in science education, concentrating on studies that utilized quantitative content analysis to generate network visualizations. They discovered that most of these studies were conducted in primary and secondary education settings.

Pellas et al. (2019a, 2019b) performed reviews on studies focused on AR applications developed using game-based learning models within primary and secondary education. The results of their research revealed that game-based AR is highly effective for teaching STEM subjects, as it aids in visualizing abstract, invisible, and complex concepts in three dimensions. More recently, Mystakidis et al. (2021) examined the use of AR technologies to support STEM learning among higher education students. They analysed 45 articles published between 2010 and 2020 in order to reveal which instructional methods were used in AR research, and found that AR technologies were generally applied to subjects related to engineering and science rather than technology and mathematics. AR was shown to be used for visualization to demonstrate situations or systems that cannot otherwise be observed conveniently in the real world. In the examined studies, presentation and activity-based methods were generally used as instructional strategies, whereas observation technique was used as the instructional technique.

AR in Mathematics Education

Kellems et al. (2020) emphasize the significant advantages of AR for mathematics education due to its distinctive characteristics. Traditionally, mathematics has been taught through non-digital means such as pen and paper and matching hardware such as a blackboard/whiteboard, or more recently, a smartboard (Lai & Cheong, 2022). However, with AR that is able to provide visualization, manipulation, and authentic context, it can be claimed that AR has a suitability for use within mathematics education (Estapa & Nadolny, 2015). According to Estapa and Nadolny (2015), AR provides effective instructional practices through a) facilitating learning engagement, b) providing situate learning, c) allowing immersion in content, d) providing authentication, and e) enhancing community building. In fact, the literature provides numerous examples that demonstrate the benefits of AR usage within mathematics education.

AR can be said to facilitate the learning of topics where visualization is deemed important (Lai & Cheong, 2022). It enhances the learning of complex subjects by providing 3D simulations of conditions that are otherwise tough to see in mind's eye (Cai et al., 2020), and that can only be presented in 2D through textbooks or other printed materials (Özçakır & Çakıroğlu, 2021). Due to its ability to blend physical objects with digital elements, AR facilitates the integration of mathematical problems into real-world contexts or vice-verse, aiding students in solving mathematical problems they encounter in their daily lives (Cevikbas, 2023). Moreover, AR technologies are considerably beneficial for use in topics in which spatial arrangement is important or where dynamic changes are included. AR may therefore be said to help students to enhance their mathematical literacy and abstract relational thinking (Lai & Cheong, 2022). The incorporation of AR in mathematics education enhances student interaction and allows students to examine objects in greater detail and from various perspectives. (Estapa & Nadolny, 2015). Moreover, learning mathematics becomes more fun and motivational when AR applications are implemented (Corrêa et al., 2013; Demitriadou et al., 2019). Furthermore, AR makes abstract math concepts concrete. For example, the "cleARmaths" app facilitates the learning process for abstract concepts such as vectors by using three-dimensional visualization in teaching geometry (Schutera et al.,2021. Research has shown that the usage of AR in mathematics education can provide an interesting learning experience, helping students to develop a positive attitude toward mathematics, and enhancing student-teacher collaboration and learning in geometry (Billinghurst & Duenser, 2012; Lin et al., 2015; Kaufmann & Schmalstieg, 2003), as well as manipulative (Bujak et al., 2013) and basic computation (Lee & Lee, 2008). Sun and Chen (2019) showed that the use of AR in mathematics education improves student interaction with peers and learning materials. Also, they stated that because AR tools or applications requires less cognitive effort, students' participation in learning activities is increased, hence AR increases learning performance with an indirect way. In addition, AR provides students with the opportunity to learn mathematics at their own pace and personalizes the learning experience according to their individual needs. For example, a student struggling with algebraic equations can use AR to visualize and interact with variable manipulations, making abstract concepts more concrete and understandable (Bulut & Borromeo, 2023). Liao et al. (2015) utilized an AR application to teach geometric concepts and reported improvements in students' attitudes towards learning geometry and mathematics, as well as enhanced achievement in geometry. Similarly, Cai (2018) observed that students developed a positive attitude towards the use of AR and demonstrated increased reasoning skills and academic success. Additionally, Estapa and Nadolny (2015) found that AR not only boosted student achievement but also heightened their motivation to learn mathematics. Ahmad and Junaini (2020) conducted a systematic review of research that investigated the use of AR in mathematics education with an analysis of 19 research articles published between 2015 and 2019. Research indicates that the use of AR in mathematics learning improves students' comprehension and confidence, enhances their visualization skills, and offers an interactive learning experience (Chen, 2019; Gecu-Parmaksiz & Delialioglu, 2019; Lin et al., 2015). Similarly, Palancı and Turan (2021) in their literature review found that AR usage in mathematics education is associated with improved learning, spatial abilities, and motivation. However, they also identified technical difficulties and the challenge of developing suitable materials as significant drawbacks.

In addition to the many positive aspects mentioned here, there are also certain difficulties in using AR within the mathematics education process. In some studies, there were cases reported where the participant groups were of only a small size at the application stage due to a lack of appropriate technical infrastructure (e.g., limited numbers of tablet personal computers, or smart-glasses) (Özçakır & Çakıroğlu, 2021; Sırakaya & Alsancak Sırakaya 2022)). Another difficulty conveyed in the literature relates to the type of platform upon which AR software is used. For example, designing software for Android that is also usable in the iOS operating system requires starting the design process all over again (Ibili et al., 2019). Additionally, in the study of Moreno et al. (2021), some students were found to focus their attention on the application itself, rather than on the basic components of the subject being learned. These difficulties reveal that both design and content development require human and financial resources, as well as pertinent knowledge in the use of AR apps in mathematics teaching.

Method

Design of the Study

In the current study, a systematic review method was applied to examine studies that utilized augmented reality in mathematics education. This method focuses on research questions and examines studies from the literature based on certain qualifications (Bearman et al., 2012). Early career researchers, and especially researchers new to a certain field of study, should familiarize themselves with the available literature on a particular topic in order to acquire a broader spectrum of thought on the subject. The systematic review is considered an effective way to achieve this aim (Zawacki-Richter et al., 2020).

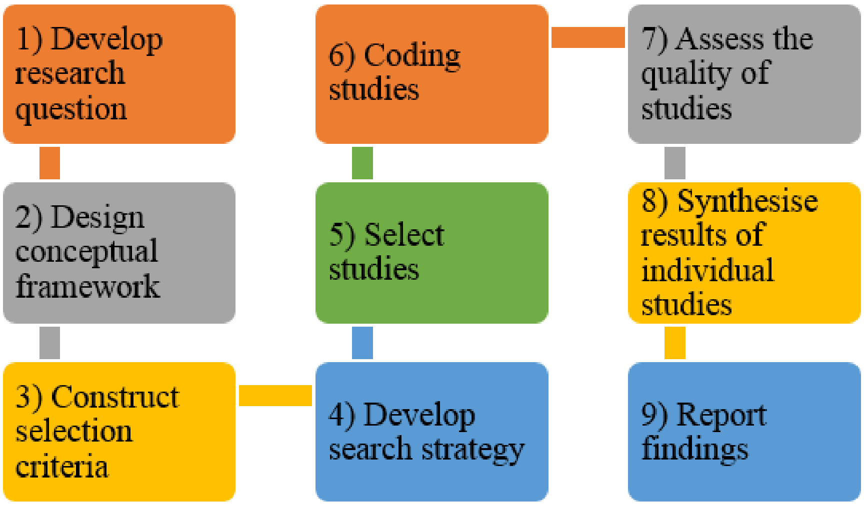

Figure 2. Systematic Review Process

In this systematic review study, researchers followed up the process, as illustrated in Figure 2, as suggested by Newman & Gough (2020, p. 6). The research questions were developed by the research team as the first stage of the process. Next, the selection criteria were determined as containing the words "augmented reality" and "mathematics" (including sub-learning areas) either in the title or keywords of the published studies. Another selection criterion was that studies had to be peer-reviewed research articles that applied AR technology. In other words, studies such as surveys, meta-synthesis, books/chapters, and conference presentations were excluded.

As a time interval, it was decided to investigate studies published between 2010 and 2024. In order for the current research to be executable and easy to control, the preferred search strategy was to examine articles listed in the Web of Science, ERIC, and SCOPUS databases. Determination of studies according to the selection criteria, as the next stage of the review process, is explained in the following subsection.

Data Collection

In this research, articles related to AR and mathematics listed in the Web of Science, ERIC, and SCOPUS databases were selected as data sources. As a filter, the publication language was chosen as English, the research article option was selected, and the date of publication was limited to between January 2010 and June 2024. When performing searches on the databases, the following words and their various combinations (in the form of "technology used and mathematics or learning fields," e.g., augmented reality and mathematics education) were used as keywords:

- Augmented reality
- Mixed reality
- Mathematics education
- Mathematics
- Geometry
- Probability
- Algebra

During the systematic search process summarized in Table 1, the specified keywords and their combinations were used to search the databases. This search yielded a total of 645 items: 415 from the Web of Science database, 113 from the ERIC database, and 117 from the SCOPUS database. A total of 21 items were excluded from the study, either because they could not be accessed in full (i.e., abstract only) or because they were publications other than a research article (e.g., book, book chapter, conference paper, editorial note, etc.).

Table 1. Steps of systematic review process in article selection

	Database		
Steps	WoS	ERIC	SCOPUS
Initial search result	415	113	117
Total after removal of inaccessible and non-article publications	623		
Total after removal of duplicate articles	526		
Total after removal of irrelevant articles based on title and abstract review	152		
Total after removal of irrelevant and beyond focus articles after reading the full text	96		

Of the remaining 623 items, 97 were found to have been repeated within the three databases, and were therefore also excluded from the study. From the 526 articles that remained at this stage, a further 374 were then excluded since their article title and abstracts, upon examination, were found to be unrelated to the objectives sought in the current study's research questions. To put it more bluntly, if a study contains independently both the words mathematics and AR, it would appear in the search outcomes. However, studies that were not relevant to the application of AR in mathematics education were excluded. Subsequently, the full texts of the remaining 152 studies were reviewed. Of these, 56 papers, including meta-analyses, systematic reviews, theoretical frameworks, and content development studies, were omitted as they did not meet the required criteria. As a result, a total of 96 articles were examined in the current study. In order to systematically identify and record the information from the papers that aligns with objectives of the review, the metrics used in this review and the process followed are detailed in the following section.

Coding and Analysis Procedure

After identifying the studies to be analysed, a coding sheet was developed by all researchers to describe specific features and content of papers based on the suggestions of Newman and Gough (2020). Draft version of the coding sheet contained 3 main parts; a) basic information, b) AR tools and c) results. Additionally, other sub-parts are shown in Table 2.

Table 2. Main Parts and Sub-parts of Coding Sheet

	Main Parts		
	Basic Information	AR tools	Results
Sub-Parts	Index	Platform SDK (added)	Control group details
	Publication year	Who developed	Summary
	Country	Hardware	Benefit – drawbacks
	Citation details	Usage Objective(s)	Limitations
	Key words		Remarkable sentence
	Aim		
	Learning area		
	Topics and/or Concepts		
	Participants		
	Research method		

As part of the pilot work, five studies were independently coded by the researchers using the coding sheet. After discussions among the researchers, it was decided to include the platform details of the AR software and to proceed with coding using these subparts. This decision was based on the observation that such information is typically mentioned in articles. And also, it was thought that it will make a contribution to the purpose of the research. The remaining 91 articles were reviewed and coded by two mathematics education researchers. Subsequently, two experts in computer and instructional technology reviewed the coded data and provided feedback.

After the coding phase was completed, the researchers came together to analyse, organize and report the findings. The coded data were analysed using content analysis, a method commonly used in literature reviews to categorize and compare textual information (Krippendorff, 2018). Krippendorff (2018, p.196) suggests 'Analytical/Representational Techniques' to analyse. According to these techniques, firstly, the coded data were summarized with descriptive information. After that, patterns and relationships were tried to be discovered. Finally, it was aimed to support the results of other studies or introduce additional perspectives by making comparisons with the findings of prior studies. The findings are given in the next section.

Findings

Based on a review of studies on AR in mathematics education, Figure 3 provides an overview of the classification of AR usage across various dimensions in this field. In the subsequent subsections, the trends in AR applications in mathematics education are examined across several categories to offer detailed information. Initially, the analysis focuses on the number of publications by year, the educational levels where AR was implemented, and the mathematics topics addressed in the AR materials.

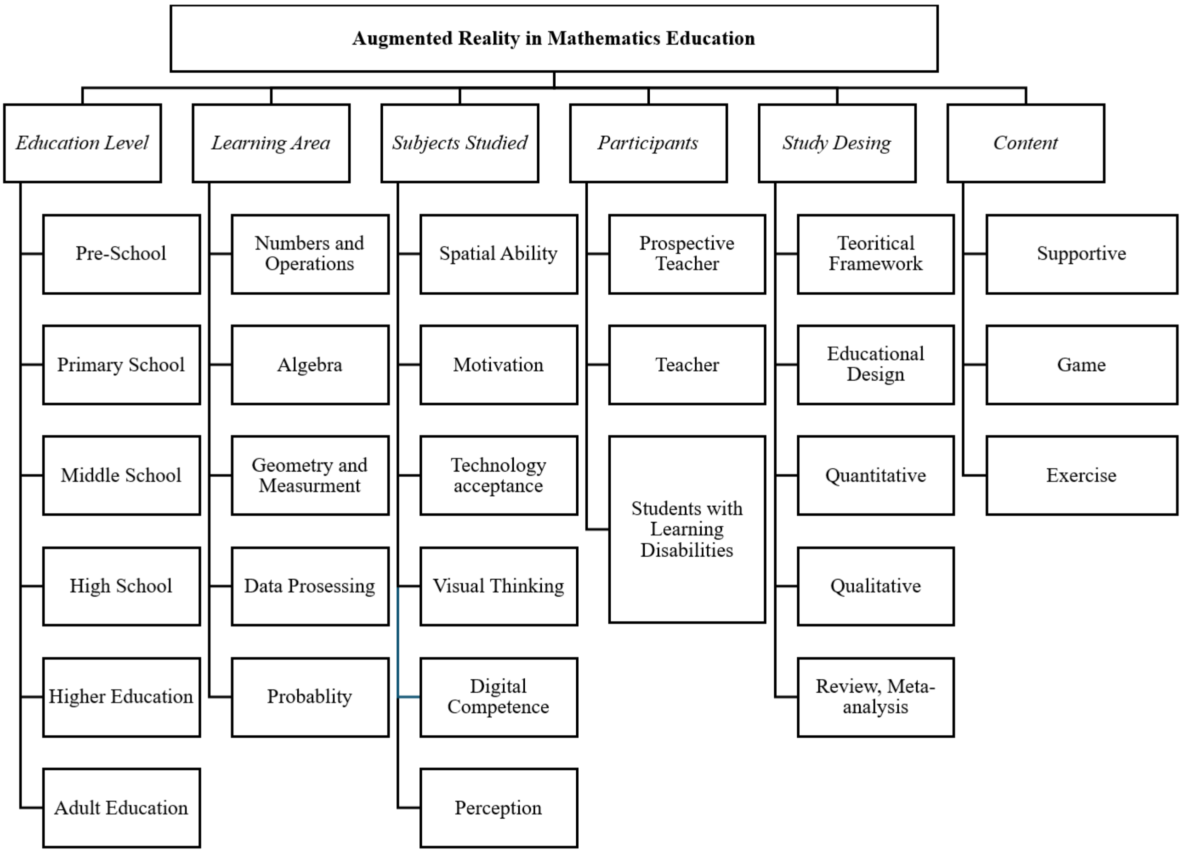

Figure 3. Classification of AR use in mathematics education

Number and Research Design of Articles Published by Years

Of the 96 studies included in the current study, one was published in 2014, four in 2015, two in 2016, four in 2017, three in 2018, 16 in 2019, 16 in 2020, 18 in 2021 (the year with the most studies), 10 in 2022, 17 in 2023 and 5 in 2024 (up to June). In Figure 4., the distribution of the articles per year from 2014 to 2024 (June) is presented. When the graph is analysed, it is observed that the increase continues almost every year up to 2021, but fluctuations are observed in the subsequent years. Additionally, it can be seen that, excluding 2022 due to the necessary reduction in practical studies caused by COVID-19, the graph almost flattens from 2019 to 2023 similar with the result of Erşen and Alp (2024). Two possible options come to the forefront here: i) either augmented reality studies have truly reached saturation and will not increase further, or ii) the disruptions in educational research due to the COVID-19 global pandemic have caused irregularities, and this flattening may be temporary. To make a definitive decision on this matter, it is necessary to wait and analyse a few more years. The continuous increase until 2021 indicates a year-on-year rise in the number of publications, as noted by Akçayır and Akçayır (2017) and Garzón et al. (2019). Notably, although Palancı and Turan (2021) reported that qualitative studies were more prevalent, Figure 4 reveals that the majority of studies on AR in mathematics education were quantitative. However, it is observed that the number of quantitative studies has decreased since 2019. The decrease in quantitative studies since 2021 may be one of the effects of the COVID-19 pandemic. The pandemic likely made quantitative research methods, such as practical and field studies, more difficult to conduct.

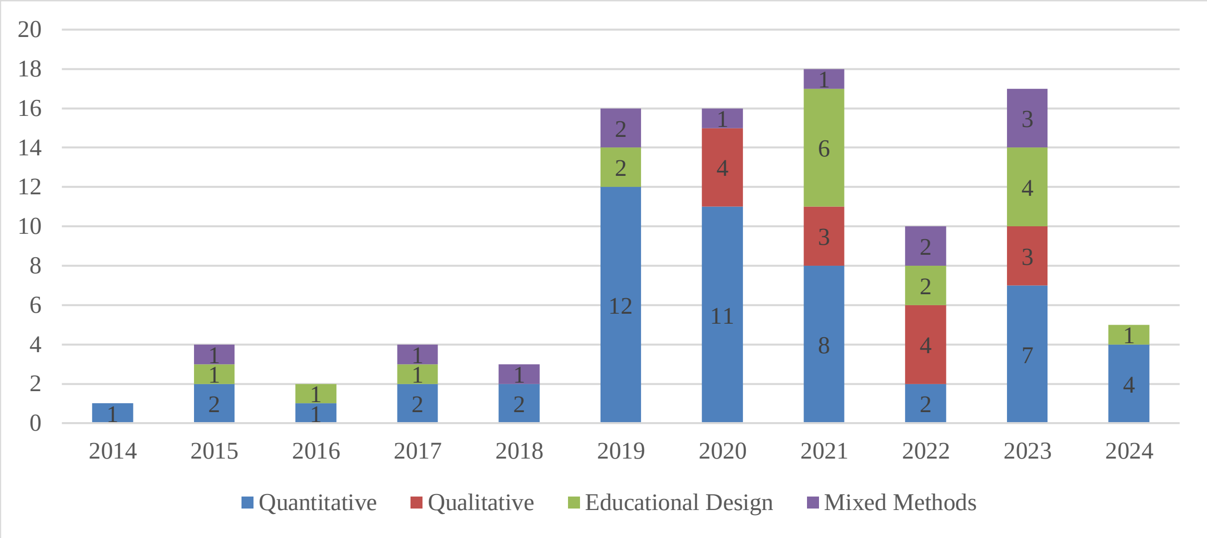

Figure 4. Number of Studies by years and design

Participants of Studies

Figure 5 depicts the educational levels at which the studies were conducted, while Figure 6 shows the number of participants involved.

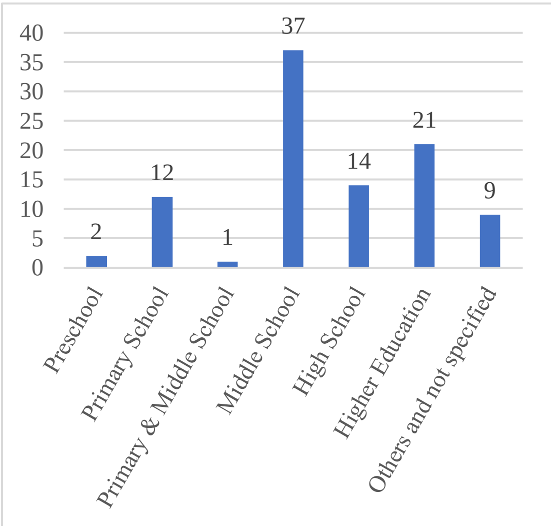

Figure 5. Distribution by school type

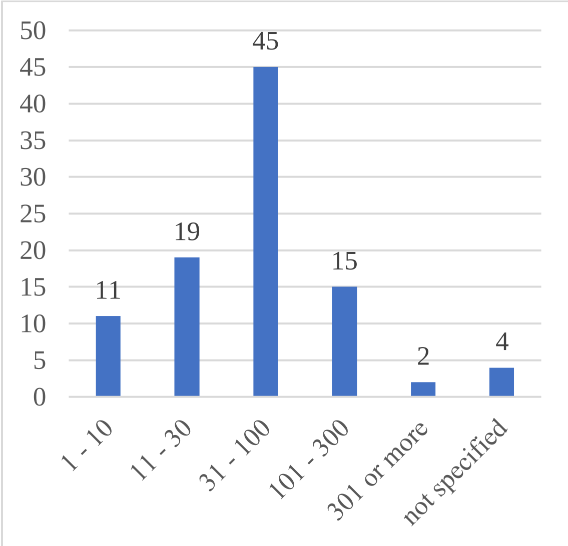

Figure 6. Number of Participant

Analysis of the participants' educational levels reveals a predominant focus on middle school and university students similar to the result of Bulut and Ferri (2023) and Erşen and Alp (2024). Aligning with the findings of Garzón et al. (2019), none of these studies targeted postgraduate students. This observation highlights a significant gap in the research, suggesting that postgraduate students have been neglected as a primary demographic. When analysing the number of participants, it becomes apparent that the majority of studies were conducted with 31-100 participants, contrary to what Bulut and Ferri (2023) reported. This finding indicates a preference for conducting studies with a limited number of participants, with larger-scale participant groups being seldom utilized. Such a trend highlights the need to consider the implications of sample size on the generalizability of the research findings. It underscores the importance of evaluating how the design and scale of these studies impact the broader applicability and validity of their results.

Mathematics Learning Areas Covered in AR materials

Figure 7. shows the percentages of AR usage across the broad field of mathematics education.

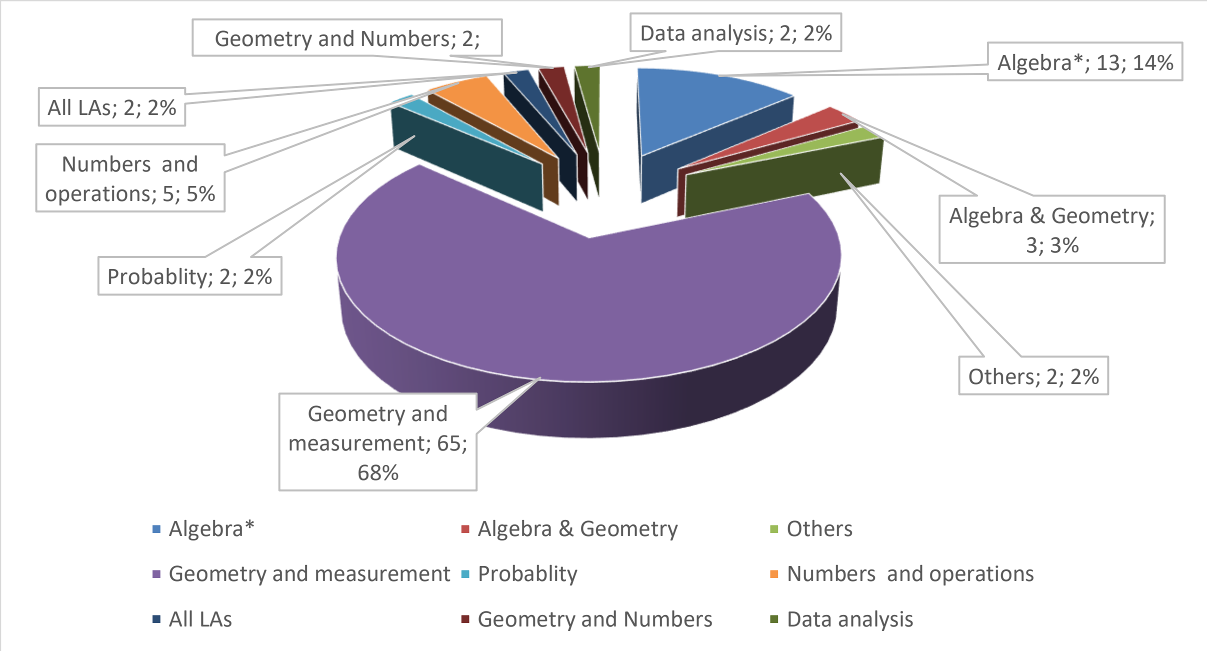

Figure 7. Distribution by Mathematics Learning Areas (Note: To reduce complexity, topics such as derivative and integral are included under algebra)

In most of the studies examined, AR was applied in the topics of geometry and measurement. This result supports the findings reported in prior research (e.g., Ahmad & Junaini, 2020; Bacca et al., 2014; Blake & Butcher-Green, 2009; Bulut & Ferri 2023). Therefore, geometry and measurement learning area continue to maintain their popularity in augmented reality (AR) studies. These areas are frequently explored due to their potential for enhancing spatial understanding and providing interactive learning experiences. One reason for this finding may be that the 3D designs of many geometric objects are suited to the AR environment, with AR designs helping students to visualize and complement their own mental images (Kaufmann, 2004). Also, geometry and measurement require spatial understanding and visualization. AR technology offers visual and interactive tools to enhance these skills. Researchers believe that these visual and interactive elements can help students better grasp abstract concepts. This rationale may explain why the domains of geometry and measurement are the most preferred learning areas in AR studies (Ibáñez et al., 2014).

Countries Where Studies Were Conducted

Upon analysing the countries where AR studies were conducted, it becomes evident that the majority of these studies took place in Türkiye, Indonesia, the United States, Mexico, Spain and Taiwan, respectively, as illustrated in Figure 8. This finding supports those of Erşen and Alp (2024), who also reported that most studies were conducted in Turkey, followed by Indonesia. However, this distribution contrasts with the findings of Palancı and Turan (2021), who reported that AR studies were predominantly conducted in Mexico, Taiwan, and Spain. Additionally, our findings contradict those of Bulut and Ferri (2023), who reported that most studies were conducted in the United States.

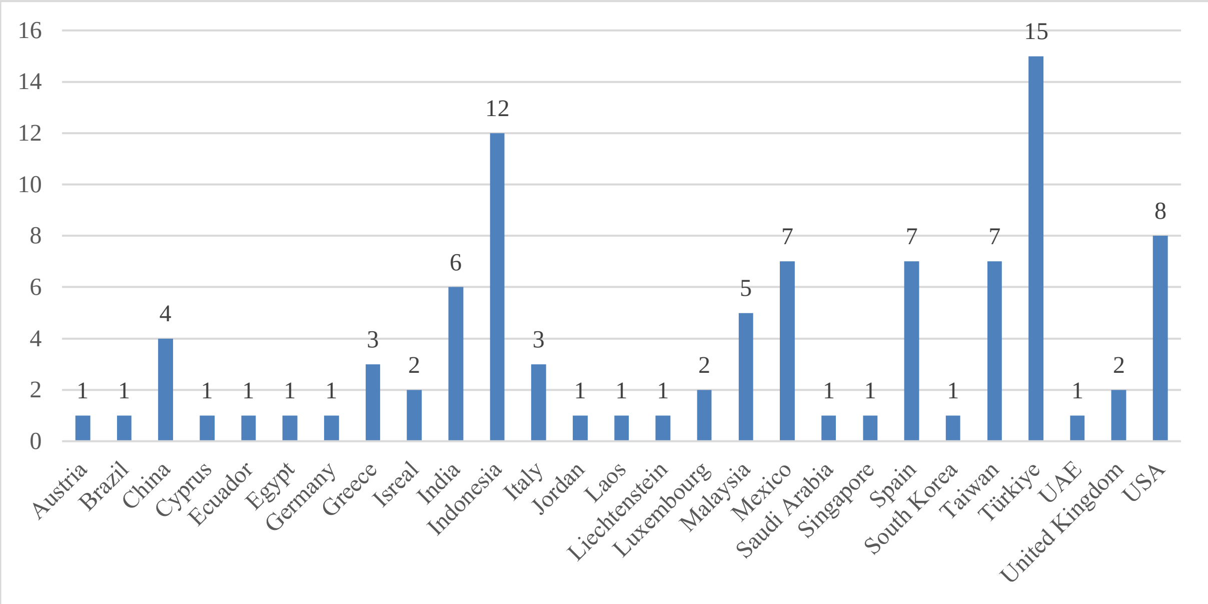

Figure 8. Studies by Countries

The discrepancy between these findings highlights a potential shift in research trends and geographical focus over time. It suggests that recent studies have increasingly been conducted in Türkiye and the United States, thereby broadening the scope of AR research beyond the regions previously identified. This change may reflect evolving research priorities, resource availability, or institutional interests in these countries. Further exploration of the factors contributing to the geographical diversification of AR research could offer valuable insights into the global advancement and application of AR technologies.

Benefits of AR Usage in Mathematics Education

Table 3 outlines the subjects explored in studies on the use of AR in mathematics education. Beyond the impact of AR technology on students' academic performance, findings indicate that AR positively influences students' attitudes and interest in mathematics, motivation, spatial abilities, creative thinking skills, use of high-level strategies, self-efficacy, critical thinking skills. AR applications also provide benefits in reducing anxiety and improving time efficiency.

Table 3. List of subjects dealt with in reviewed studies

Subject	Number of Articles Mentioned in *
Academic performance	62 (59 increased, 3 unchanged)
Spatial ability	24 (all increased)
Motivation	23 (22 increased, 1 partly increased)
Attitude	7 (all increased)
Interest	3 (all increased)
Creative thinking skills	2 (both increased)
High-level strategy use	6 (all increased)
Self-efficacy	2 (both increased)
Critical thinking skills	1 (increased)
Anxiety	1 (decreased)
Time consuming	1 (decreased)

*Some articles mention more than one subject

According to Table 3, AR mostly (and almost always positively) affected academic performance, in a similar vein to the findings of Bulut and Ferri (2023) and Erşen and Alp (2024). This was followed by a positive effect on students' spatial ability, motivation, and other subject areas. Based on this table, it is seen that AR has many positive effects in mathematics education. Especially in areas such as academic performance, spatial ability and motivation, the positive effects of AR have been frequently emphasized in the reviewed studies. Moreover, no negative effects have been reported. This indicates that AR can be a valuable tool in educational settings, providing significant benefits without causing harm.

Purposes of AR Usage in Mathematics Education

Upon examining the purposes for which AR was utilized in the reviewed studies, it is apparent that AR software and applications have been employed for a variety of objectives within the realm of mathematics education, as detailed in Table 4. The vast majority of these studies leveraged AR applications as educational material, indicating their use directly as an intervention tool in mathematics courses. This suggests that AR was integrated into the curriculum to enhance instructional delivery and student engagement.

Table 4. Purpose of AR usage in Mathematics Education

Purpose	Number of Articles
Educational material	82
Game	8
Supportive and exercise	1
Creating educational material	5

Furthermore, several studies explored the use of AR applications in different capacities. Some utilized AR as a gaming tool, aiming to increase motivation and interactive learning among students. Others employed AR as supportive and exercise-based material, providing supplementary resources to reinforce mathematical concepts and skills. Additionally, AR was also used for the creation of educational materials, enabling educators to develop innovative and interactive content to facilitate learning.

This diverse range of applications underscores the versatility of AR technology in educational contexts, particularly in mathematics education. The findings indicate a broad spectrum of implementation strategies, each aimed at improving pedagogical outcomes and enriching the learning experience. Such variations in AR usage highlight the potential for further research to explore and optimize these applications in diverse educational settings

To briefly summarize the results of study, although the number of studies on AR in mathematics education had increased up until recent years, it has nearly plateaued in the last few years, possibly due to temporary reasons. Additionally, quantitative studies are generally conducted. AR studies are mostly conducted with middle school students and usually with groups of 30 to 100 students. Although studies have been conducted in various countries, the two countries that stand out are Türkiye and Indonesia. In addition, there is a large amount of work related to geometry in these studies. While the use of AR as an educational material is observed in most of the studies, its effect on academic performance is mostly examined.

Discussion and Conclusion

The advancement of technology and the incorporation of AR in mobile digital devices have significantly boosted the widespread use of these devices (Laricchia, 2022), which has consequently led to the global expansion of AR development and application (Garzón et al., 2019). This trend may explain the rise in the number of studies since 2014, as indicated in the current and other review studies (Akçayir et al., 2016; Bacca et al., 2014; Chen et al., 2017; Diegmann et al., 2015; Garzón et al., 2019). According to Garzón et al. (2019), the prevalence of AR is expected to grow in tandem with the increasing use of mobile technologies.

The present study also revealed that the majority of reviewed AR studies were conducted with middle school or university students. In contrast, Garzón et al. (2019) reported that primary education students were the most frequently targeted group. According to the study's authors, AR systems allow children to learn while playing. However, such systems are complex by nature and require users to have a certain technical ability and focus, which may lead to confusion whilst using AR applications (Garzón et al., 2019). For this reason, secondary school children could have been selected as a target group since they may be considered to play just as well since they possess greater technical ability and a longer attention span compared to elementary school students. Regarding the inclusion of university level participants, Garzón et al. (2019) asserted that this level encompasses adults aged 17 to 24 years, who possess the maturity to manage technology yet still need pedagogical resources to acquire new knowledge.

Similar to the findings in educational augmented reality studies (Sırakaya & Alsancak Sırakaya, 2018; 2022), the analysis from the current study revealed a year-on-year increase in the number of publications on the usage of augmented reality in mathematics education up to 2021 (Akçayır & Akçayır, 2017; Erşen & Alp, 2024; Garzón et al., 2019). However, in 2020 and 2021, the global impact of the COVID-19 pandemic led most countries to implement e-learning strategies for education at all levels. This, in turn, may have affected the volume of AR-based studies which could explain the stability after 2021. Additionally, the current study has shown that the majority of AR studies were conducted with between 31 and 100 participants; a finding potentially caused by the research design type selected in each of these studies since the research aims often directly impact on the determination of appropriate sample size. As reported, mostly quantitative studies were conducted on the application of AR in mathematics education, which is an opposing finding to that of Palancı and Turan (2021) who stated that most studies were qualitative. On sample size, Borg and Gall (1979) proposed several criteria for the determination of sample size based on research methods. Accordingly; in relational survey designs, the sample size should be at least 30; for experimental and causal-comparative studies the sample size should be at least 50; and in survey studies at least 100 samples should be sought for each major subgroup and 20-50 samples for each minor subgroup in the population. The rationale behind choosing sample sizes in this manner may explain why the majority of studies have between 30 and 100 participants.

The current systematic review pointed out that AR applications are generally prepared for the geometry and measurement topics of mathematics courses. As stated by Kaufmann (2004), it is easy to design many different geometric objects in 3D within an AR environment, and that AR applications can help students to visualize and complement their own mental pictures; hence, AR applications may often be developed for geometry and measurement.

The majority of AR studies reviewed were found to be have been conducted in Türkiye, Indonesia, the United States, Mexico, Spain and Taiwan. In Türkiye, the FATIH project, an innovative national implementation project delivered by the Turkish Ministry of Education, introduced digital technologies such as fast Internet connection, smartboards, and tablet personal computers to integrate classrooms (Başoğlu et al., 2022), which may have encouraged researchers to integrate novel technologies such as AR into the classroom environment.

Finally, the current study demonstrated that AR can positively affect students' attitudes and interest towards mathematics, motivation, spatial ability, creative thinking skills, high-level strategy use, and self-efficacy as indicated in several research studies in the current literature (e.g., Chen, 2019; Gecu-Parmaksiz & Delialioglu, 2019; Lin et al., 2015; Palancı & Turan, 2021). In most of the studies reviewed, AR applications were used as educational material as a direct intervention tool used in mathematics courses. Additionally, in some studies, AR applications were used as a game, as supportive and exercise-based material, and for creating educational materials.

The benefits and advantages of (AR) in mathematics education, as derived from the findings of this study, can be summarized as follows. Mathematics encompasses abstract concepts that students often find challenging to grasp. AR offers students a concrete experience by visualizing these concepts, thereby enhancing their understanding. This can help students better grasp complex mathematical concepts. Furthermore, AR has an interactive nature and these interactive structures of AR offers students the opportunity to experience and explore concepts. This helps students understand concepts or problem-solving processes more deeply, rather than just memorizing them. Moreover, the innovative and interactive features of AR attract the attention of students and encourage them to engage with mathematics. This can increase the interest of students and motivation to learn mathematics. Additionally, students may feel more self-sufficient in understanding and applying mathematical concepts, therefore the interactive experiences offered by AR can give students more confidence in their own abilities. Besides, Students can see how they can solve mathematical problems in real-world scenarios because AR offers students the opportunity to demonstrate how to use theoretical knowledge in practice.

From the point of view of students' learning styles, not all students can be expected to learn in the same way. AR helps overcome this problem as it appeals to students with visual, (sometimes) auditory and kinaesthetic learning styles. Additionally, AR can be used in academically diverse classrooms because it has adaptable features for students with different learning speeds. In conclusion, using AR in mathematics education provides students with new and innovative ways of understanding, exploring and applying mathematical concepts. This approach enhances the significance, engagement, and efficacy of mathematics learning. The advantages of AR technology in mathematics education facilitate a deeper comprehension and mastery of mathematical concepts among students.

The general conclusion from the current systematic review study is that although certain limitations and difficulties may exist, such as financial, the supply of technical materials and human resources, the use of AR in mathematics education has great potential according to the trends apparent from recent research history. With the aid of technological tools and devices that continue to develop day by day, the use of AR in mathematics education is likely to become easier for users to benefit from, as well as being more widespread.

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