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Meta-Synthesis: The Use of Augmented Reality Technology as A Mathematics Learning Media

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a b s t r a c t

This study aims to review, analyze and classify articles that contain literature related to the use of augmented reality technology as a mathematics learning medium. Using meta-synthesis methodology, this research systematically reviews and interprets findings from various articles related to the integration of AR in mathematics education. Through extensive searches in the Scopus and Sinta databases, 15 relevant articles were selected based on predetermined inclusion criteria, including year of publication (2018-2023), focus on mathematics learning in schools, and the presence of AR output images. Conducting a literature review with specific keywords ('Augmented Reality in mathematics learning'). The analysis reveals AR applications/modules, visualizations, and worksheets as prevalent AR outputs in math learning. In particular, Unity 3D and Vuforia excel among diverse development tools, showcasing flexibility. The discussion underscores AR's potential for intuitive math visualizations, enhancing learning experiences, and improving comprehension of complex concepts. The main characteristics of AR are virtual environments, real-time interactivity, and 3D representation, with an attractive design that makes a positive contribution to mathematics education.

K e y w o r d s :
Augmented Reality; Learning Media; Math; Meta Synthesis

INTRODUCTION

Tondeur et al (in Lestari, 2018) stated that digital technology has now begun to be used in educational institutions as a means to support learning, either as an information tool (i.e., as a means of accessing information) or as a learning tool (i.e., as a means of supporting learning activities and tasks). Currently, there are many media or learning aids that use ICT, one of which is mathematics subjects (Mursyidah, et al., 2022). According to Munir (2012), media can develop sensory abilities and attract attention and interest. Media can also present information that can be seen, heard, and acted upon, so that media is very effective as a complete tool in the teaching and learning process. The advantages of media effectiveness can be seen in several aspects, as stated by Munir (2012), including: (a) It is multisensory because it stimulates many of the senses, so it can lead to good attention and retention levels, (b) Attracts attention and interest because it is a combination of sight, sound, and movement, (c) Interactive nature creates a two-way relationship between media users. Interactivity allows developers and users to create, manipulate, and access information. By using media, mathematical concepts and symbols that were previously abstract become concrete, allowing us to introduce mathematical concepts and symbols from an early age, adjusted to students' level of thinking (Farihah, 2021).

With advances in technology, we can also explore opportunities for applying technology such as Augmented Reality (AR) in the context of mathematics learning. James R Valino quoted from Mustaqim (2016) explained that Augmented Reality is a technology that combines two-dimensional or three-dimensional virtual objects and then projects these virtual objects in real time. AR combines the real world with digital elements, so students can see mathematical concepts in a more visual and interactive way. By using AR in mathematics learning, students can visualize mathematical objects that are difficult to visualize, as researched by Hardiyanti, D., Rosyadi, R., & Mellawaty, M. (2020).

Augmented Reality (AR) is interactive and applicable to learning, providing a better understanding of concepts, creating a real learning environment, and offering a higher quality learning experience. With AR, students have the opportunity to interact with 3D objects as virtual entities (Hardiyanti, 2020). AR, as a learning medium, is designed to be as interesting and communicative as possible, inviting students to engage in multi-sensory activities (involving more than one sense) (Pangestu et al., 2019).

According to Mareta (2015), there are two types of Augmented Reality available for teachers to use as media: Location-based: Utilizing GPS technology installed on smartphones, this media displays information, narratives, navigation, or architectural models related to the real world. Students can visualize digital maps and physical areas. Visual-based: Displayed as a virtual object after the learner places the camera on a marker or object (such as a QR code or 2D target). Three main benefits can be obtained from AR in mathematics learning: (i) increasing self-confidence and understanding; (ii) improved visualization; (iii) interactive learning. The application of AR technology in mathematics learning not only makes learning more interesting but also helps students understand and remember mathematical concepts better. This is because the visual and interactive experiences that AR offers can strengthen in-depth understanding of concepts.

From the description above, the researcher conducted systematic review research by collecting several articles with predetermined keywords. The purpose of this research is to review, analyze, and classify articles that contain literature related to the use of augmented reality technology as a mathematics learning media. More clearly, in Table 1, the research questions (PP) for this study have been formulated.

Table 1
Research Questions

PP	Research Questions
1.	How is the output form of augmented reality media in mathematics learning?
2.	Design and characteristics of Augmented Reality-based media?
3.	What types of developer tools are used to develop augmented reality technology as a mathematics learning media?
4.	What are the benefits of Augmented Reality in mathematics learning?
5.	What are the common mathematics learning topics that often use Augmented Reality technology?

METHODS

Reseach Design

Meta-synthesis, also known as a systematic review, is a research method to find, evaluate, and interpret results from similar studies to address specific research questions, topics, or current phenomena (Kitchenham in Siswanto, 2010). This kind of data is then carefully identified, analyzed, and interpreted to draw meaningful conclusions. Using a meta-aggregation approach, a meta-synthesis study is used to bring together diverse research outcomes associated with the Augmented Reality (AR) technology theme. As outlined by Lewin (2008), the purpose of meta-aggregation is to address research questions, helping to compile aggregates derived from various research results relevant to the specified theme. In the search for articles related to the research theme, specific keywords are used, namely: "Augmented Reality in mathematics learning."

The chosen research procedure follows the meta-synthesis methodology described by Korkmaz & Morali (2022), covering: (1) meta-synthesis design, which involves determining objectives, subjects, and research questions, (2) literature review, covering literature search using predefined criteria (inclusive-exclusive) and assigned keywords, (3) scrutiny and evaluation of articles, focusing on content pertinent to AR, (4) data analysis, involving the organization of categories and sub-categories based on research questions, (5) synthesis, involving the amalgamation and synthesis of diverse research findings, and (6) reporting and presentation, summarizing various research outcomes and engaging in discussions that draw comparisons with similar studies.

During the article selection phase, a thorough literature review was conducted on articles published in journals indexed in both Scopus and Sinta, exploring topics related to "Augmented Reality in Mathematics Learning." The selection process considered the year of publication, with a primary focus on articles published within the last 6 years, spanning from 2018 to 2023. Establishing the inclusion criteria is a key step to streamline the search for studies in the subsequent phase. All the studies gathered during the initial search underwent thorough examination and evaluation based on the predetermined inclusion criteria designed for their incorporation into the meta-analysis. The inclusion criteria outlined in this meta-analysis encompass:

1. The year of publication range from 2018 to 2023;
2. Indonesian studies in the form of articles published in national or international journals;
3. Specific to mathematics learning in schools;
4. The article contains augmented reality and has output images from the research

Furthermore these articles will be presented in a structured manner addressing all criteria predetermined earlier

Data Collection

Analysis of the 15 selected articles will be presented sequentially based on the components to be analyzed in each article. Evaluation data will be processed following the previously outlined steps to obtain significant results from this research. The data from the 15 analyzed articles are listed in the following table.

Table 2
List of Articles

Article	Title	Authors
A1	Mathematics learning instrument using augmented reality for learning 3D geometry	R N Auliya and M Munasiah (2019)
A2	An Augmented Reality Application for Basic Mathematics: Teaching and Assessing Kids' Learning Efficiency	Manisha and Mantri A. (2019)
A3	Hand ControlAR: An Augmented Reality Application for Learning 3D Geometry	Rui Cao, and Yue Liu (2019)
A4	Digital Game Based Learning using Augmented Reality for Mathematics Learning	Fadila Aulia Pritami and Izzati Muhimmah (2018)
A5	Designing augmented reality-based mathematics mobile apps for outdoor mathematics learning	M G K Ahsan, Miftahudin, A N Cahyono (2020)
A6	Augmented Reality-based Mathematics Worksheet for Online Learning During Covid-19 Pandemic	Soma Salim S, Fitrah A. Darmawan, Jainuddin (2020)
A7	ARMath: Augmenting Everyday Life with Math Learning	Seokbin Kang, Ekta Shokeen, Virginia L. Byrne, Leyla Norooz, Elizabeth Bonsignore , Caro Williams-Pierce, Jon E. Froehlich (2020)
A8	Learning Calculus with Augmented Reality and Virtual Environments	Linda Margarita Medina Herrera, Marlene Aguilar Abalo, Saúl Juárez Ordóñez (2019)
A9	VECTOR AR3-APP -A GOOD-PRACTICE EXAMPLE OF LEARNING WITH AUGMENTED REALITY	Karin Langer, Stefanie Lietze, Gerd Ch. Krizek. Fachhochscule Techniku (2020)
A10	Multimedia augmented reality game for learning math	Cristina Rebollo, Inmaculada Remolar, Veronica Rossano, Rosa Lanzilotti (2022)
A11	Designing prototype model of virtual geometry in mathematics learning using augmented reality	S Syafril, Z Asril, E Engkizar, A Zafirah, F A Agusti, Sugiharta (2021)
A12	PERANCANGAN BUKU ELEKTRONIK PADA PELAJARAN MATEMATIKA BANGUN RUANG SEKOLAH DASAR BERBASIS AUGMENTED REALITY	Qadhli Jafar Adrian, Agus Ambarwari, Muharman Lubis (2020)
A13	Pengenalan Bangun Ruang Menggunakan Augmented Reality sebagai Media Pembelajaran	Indah Purnama Sari, Ismail Hanif Batubara, Al Hamidy Hazidar, Mhd Basri (2023)

A14	On the Potential of Augmented Reality for Mathematics Teaching with the Application cleARmaths	Stefanie Schutera , Marc Schnierle, Mathilde Wu, Tim Pertzel, Jonathan Seybold, Patricia Bauer, Dennis Teutscher, Matthias Raedle, Natascha Heß-Mohr, Sascha Röck and Mathias J. Krause (2021)
A15	Tablet-based AR technology: Impacts on students' conceptions and approaches to learning mathematics according to their self-efficacy	Su Cai, Enrui Liu, Yang Yang and Jyh-Chong Liang (2019)

RESULT AND DISCUSSION

Implementation of AR Technology in Mathematics Learning

The utilization of Augmented Reality (AR) introduces various technologies that can enhance the learning process in educational institutions. Based on the literature review conducted, it is evident, as summarized in the table, that these technologies generally come in different forms compatible with devices such as Android, iOS, and tablets.

Table 3
The utilization of AR media based on the format or output of representation

Output AR	Article
Game Application	A2, A4, A10
Application/Module Visualizing	A1, A3, A5, A7, A8, A9, A10, A11, A12, A13, A14, A15
Worksheets	A5, A6

In the 15 analyzed articles, the application/module visualizing shapes into AR output is the most widely used in mathematics learning.

Design and Characteristics of Augmented Reality-Based Media

Augmented reality mathematics learning media design discusses interface design (UI/UX) and integration with the environment (environment integration). This means that AR-based media design presents an intuitive and responsive user experience, facilitating user interaction with AR content. The design should also consider how AR elements blend with the surrounding physical environment to provide a seamless experience. In this context, the three main characteristics of AR include the merging of the real and virtual worlds, real-time interactivity, and in three-dimensional form. Overall, a thoughtful integration between AR design and its characteristics can result in a more satisfying and effective AR experience.

Table 4
Description of Characteristics

Article	Description of Characteristics
A1	The technology of Augmented Reality (AR) in this research encompasses three main characteristics. First, there is the merging of the real world and the virtual world, manifested in AR's ability to help students visualize geometric objects in three dimensions. Second, real-time interactivity is reflected in the use of AR in mobile learning, aiming to enhance efficiency and effectiveness in the learning process. Third, representation in three dimensions can be identified through the use of Sketchup software for drawing geometric objects and AR applications for viewing objects in 3D.

	Thus, this AR technology reflects the characteristics of merging the real world and the virtual world, real-time interactivity, and representation in three dimensions.
A2	The Augmented Reality (AR) technology in this study encompasses three main characteristics. First, there is the merging of the real world and the virtual world manifested in the creation of an application called Mathify, an augmented reality app designed to assist children in learning basic mathematics, particularly counting. Second, real-time interactivity is reflected in the child-friendly approach of the application, utilizing augmented reality technology to address children's fear of mathematics. Third, representation in three dimensions can be identified through the use of augmented reality in creating effective solutions for teaching the fundamentals of mathematics to children aged 3-5 years.
A3	The Augmented Reality (AR) technology in this study encompasses three main characteristics of AR. Firstly, there is the merging of the real and virtual worlds manifested in AR's ability to provide an intuitive way of learning geometry by enabling direct manipulation of 3D objects. Secondly, real-time interactivity is reflected in the use of AR systems that allow students to naturally and directly manipulate 3D objects through gesture-based interactions. Thirdly, representation in three dimensions can be identified through the three-tier design of the study to facilitate the learning of geometric concepts and experiments to evaluate the effectiveness of the AR system.
A4	The Augmented Reality (AR) technology in this research encompasses three main characteristics of AR. Firstly, there is the merging of the real world and the virtual world manifested in the development of game-based learning applications using Augmented Reality (AR) for mathematics education. Secondly, real-time interactivity is reflected in the use of sensors such as gyroscopes, accelerometers, and GPS to support location-based Augmented Reality technology. Thirdly, representation in three dimensions can be identified through the use of Unity 3D and Augmented Reality technology in the development of learning applications.
A5	The Augmented Reality (AR) technology in this research encompasses three main characteristics of AR. Firstly, there is the merging of the real world and the virtual world manifested in the ability to create virtual objects in real-life environments. Secondly, real-time interactivity is reflected in the design of applications specifically tailored for outdoor mathematics learning, focusing on spatial geometry. Thirdly, representation in three dimensions can be identified through the use of 3D models designed to assist students in mathematically depicting real-world problems.
A6	The Augmented Reality (AR) technology in this research comprises three main characteristics of AR. Firstly, there is the merging of the real world and the virtual world, manifested in the development of Augmented Reality (AR)-based math worksheets. Secondly, real-time interactivity is reflected in the application testing using three ISO 25010 characteristics: functional suitability, compatibility, and usability. Thirdly, representation in three dimensions can be identified through the use of Augmented Reality technology in creating math worksheets.
A7	The ARMath technology possesses three main characteristics of Augmented Reality (AR). Firstly, the system leverages advanced computer vision to recognize everyday objects and visualize their mathematical attributes. Secondly, ARMath transforms these objects into tangible or virtual manipulatives, creating an interactive experience. Thirdly, using these

	manipulatives, children can solve mathematical problems that place operations or mathematical concepts in specific everyday contexts. Thus, ARMath encompasses three key AR characteristics: merging the real world and the virtual world, real-time interactivity, and representation in three dimensions.
A8	The Augmented Reality (AR) technology in this research comprises three main characteristics of AR. Firstly, there is the merging of the real world and the virtual world manifested in the development of two tools, namely AVRAM (Remote Virtual Environments for the Learning of Mathematics) and ARC (Augmented Reality in Calculus). Secondly, real-time interactivity is reflected in the use of AR to visualize and manipulate surfaces in three-dimensional space. Thirdly, representation in three dimensions can be identified through the use of AR with activity cards for each topic in multivariable calculus
A9	The Augmented Reality (AR) technology in this research encompasses three main characteristics of AR. Firstly, there is the merging of the real world and the virtual world manifested in AR applications used to support abstract STEM content such as vectors. Secondly, real-time interactivity is reflected in the discussion of the use of AR applications to support didactic learning and self-directed learning. Thirdly, representation in three dimensions can be identified through the application of Augmented Reality to support digital learning and teaching.
A10	The AR technology in this research demonstrates three main characteristics of Augmented Reality (AR). Firstly, the merging of the real world and the virtual world is evident in the visualization approach using Augmented Reality, which combines real and virtual reality. Secondly, real-time interactivity is apparent in the creation of two AR-based mini-games for mobile platforms. Thirdly, representation in three dimensions can be inferred from the use of Augmented Reality, creating a gamified learning experience for multiplication.
A11	The virtual geometry mobile application (VirGO) designed for mathematics learning based on Augmented Reality (AR) exhibits three main characteristics of AR. Firstly, the application is capable of realistically displaying learning objects and materials. Secondly, the application integrates interactive elements through advanced features such as video, images, and animations. Thirdly, the application can enhance students' interest in mathematics learning and reduce boredom. The findings of this research affirm that VirGO, based on augmented reality, encompasses crucial AR characteristics, including the merging of real and virtual elements, real-time interactivity, and representation in three dimensions.
A12	The Augmented Reality (AR) technology in this research encompasses three main characteristics of AR. Firstly, there is the merging of the real world and the virtual world, manifested in the development of MathARbook or Mathematics AR Book, a prototype elementary school mathematics book where content is displayed in AR. Secondly, real-time interactivity is reflected in the use of AR technology that combines multimedia elements such as text, images, video, animations, and sound to provide interactive learning capabilities at various places and times. Thirdly, representation in three dimensions can be identified through the use of AR technology to display content such as plane and solid geometry.
A13	The Augmented Reality (AR) technology in this research encompasses three main characteristics of AR. Firstly, there is the merging of the real world and the virtual world, manifested in AR's ability to combine real and virtual

	states in real-time. Secondly, real-time interactivity is reflected in the use of AR technology that can provide innovation and new learning experiences in understanding and studying three-dimensional structures. Thirdly, representation in three dimensions can be identified through the use of AR technology to assist in understanding the properties and characteristics of three-dimensional structures
A14	The Augmented Reality (AR) technology in this research comprises three main characteristics of AR. Firstly, the study proposes the merging of the real world and the virtual world in mathematics education, particularly in vector geometry, using AR to provide more intuitive visualizations. Secondly, real-time interactivity is reflected in the development of the "cleARmaths" application, aimed at facilitating the learning process by providing direct example practice sessions. Thirdly, representation in three dimensions takes center stage by creating the "cleARmaths" AR application, allowing students to view and interact with geometric objects in three dimensions. Thus, this abstract reflects the characteristics of merging the real world and the virtual world, real-time interactivity, and representation in three dimensions through the implementation of AR technology in mathematics education.
A15	The Augmented Reality (AR) technology in this research encompasses three main characteristics. Firstly, AR is used to aid students in understanding mathematical concepts by merging the real world and the virtual world, providing more visual and intuitive visualizations. Secondly, real-time interactivity is reflected in the use of AR on tablets during statistics and probability lessons. Thirdly, the development of lessons with AR on tablets demonstrates an effort to bring mathematical concepts, including statistics and probability, into three-dimensional representation through AR technology. Thus, this research reflects the characteristics of merging the real world and the virtual world, real-time interactivity, and representation in three dimensions in the context of mathematics learning.

Types of commonly used development tools

Although Unity 3D is a game development platform but due to its AR add-on this makes it suitable for developing AR content, Unity 3D is a free software which has a more advanced paid version. Vuforia is a software platform that specializes in providing object recognition and tagging capabilities for Augmented Reality (AR) experiences. Blender is open source software used for 3D modeling, animation, and rendering, providing flexibility and power in visual content development. SketchUp, a software used for 3D modeling, has produced an AR-enabled version. VRSoft GmbH (senselab.io) is a company focused on virtual reality and augmentation technologies, providing innovative solutions and development tools to support AR and VR projects. Of the 15 articles, there are 9 articles that use Unity 3D to design AR content. 7 articles with Vuforia development tools, 3 articles with Blender development, 2 articles with Sketcup, 1 article with VRSoft GmbH and 1 article does not include the development tools used. can be seen in table 5.

Table 5
Development tools

Development tools	Articles
Unity 3D	A2, A3, A4, A5, A6, A7, A8, A10, A14
Vuforia	A3, A5, A6, A8, A10, A11, A14
Blender	A5, A6, A12
Sketcup	A1, A13

Other (VRSoft GmbH (senselab.io))	A9
Does not include	A15

Benefits of using augmented reality

The goals and benefits of using Augmented Reality (AR) are always present in all AR technology learning media. This is because AR can be collaborated with by developers with the aim of increasing interest, motivation and learning experience with its ability to visualize objects and provide users with the opportunity to interact directly during the learning process.

Table 6
The benefits or objectives of AR technology in mathematics learning

Benefits/Goals	Articles
Helps visualize geometric objects	A1
Improve space visualization skills	A8. A12
Increasing the efficiency and effectiveness of learning	A1, A2, A3, A4, A5, A11
Attract students' interest and understanding of the material	A1, A10, A11, A12, A13, A14
Improve spatial abilities	A3
Overcoming the negative impacts of using gadgets	A4
Helping mathematical illustrations to solve real problems	A5, A7
Learning flexibility	A6, A12
STEM learning support	A9
Motivation for learning through a game approach	A2, A4, A10
Increase self-efficacy	A15

Mathematics subject that uses augmented reality

The analysis of articles revealed that geometry is the mathematical subject that most frequently utilizes AR media, with specific media addressing topics related to spatial structures. Additionally, many articles cover numerical topics such as basic arithmetic for elementary school students. Further details are presented in the table 7.

Table 7
Mathematics Subject

Mathematics Subject	Articles
Geometry	A1, A3, A5, A7, A11, A12, A13
Geometry: Vector	A9, A14
Number	A2, A4, A10
Arithmetic	A7
Algebra	A6
Algebra: Calculus	A8
Statistics	A15

Discussion

Augmented Reality is an attempt to unite the real world with the virtual world created by computers, making it very close and integrated. This is in line with the opinion of James R. Valino quoted from Maulana, et., al. (2019), Augmented Reality is a technology that combines virtual two-dimensional or three-dimensional objects, and then displays virtual

objects in real time. Enhanced AR can be applied to various fields including education. With the rapid spread of smartphones in society, including among students, research has focused on the use of augmented reality (AR) in mobile learning. Application of augmented reality (AR) in classroom learning with a variety of interesting forms of presentation in several forms such as game applications, applications/modules, or worksheets. This is done to achieve the expected learning objectives. From the results of the analysis of 15 articles, it shows that learning with applications/visual modules is the output/form of AR presentation that is most widely used in mathematics learning. Through an AR visualization application or module, students can experience the visualization of mathematical objects in three dimensions with the help of markers. This helps them understand geometric concepts in a more realistic and in-depth way than two-dimensional representations in textbooks. Fun Interactive Experience through a game approach, Students can experience interactive and fun mathematics learning experiences through game elements in AR game applications, so output is needed in the form of games with AR technology that are relevant to the material and students' needs. The use of worksheets also involves students in solving mathematical problems using AR technology. Students can interact with their worksheets directly, creating higher engagement than traditional methods.

Figure 1
AR output in the form of game applications

Figure 1 is an example of the output of a game application that has been developed by Rebollo et al. (2022). The image shows partial graphic results when completing the mini-game (top) and a summary of the end of the application (bottom).

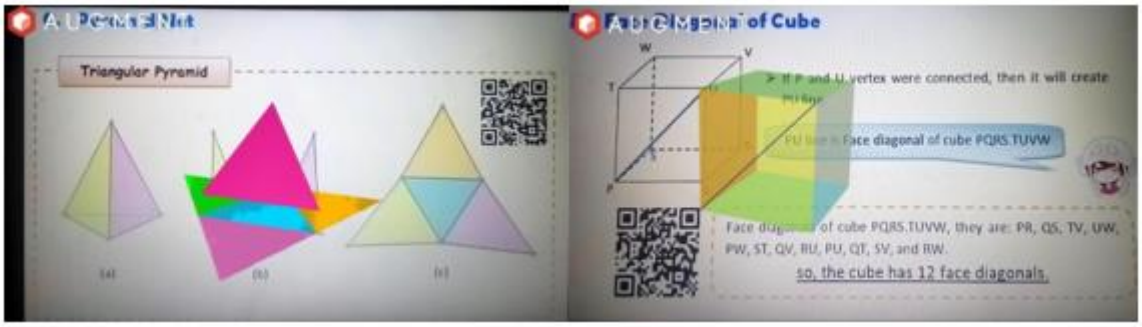

Figure 2
AR output in the form of Visualizing Module

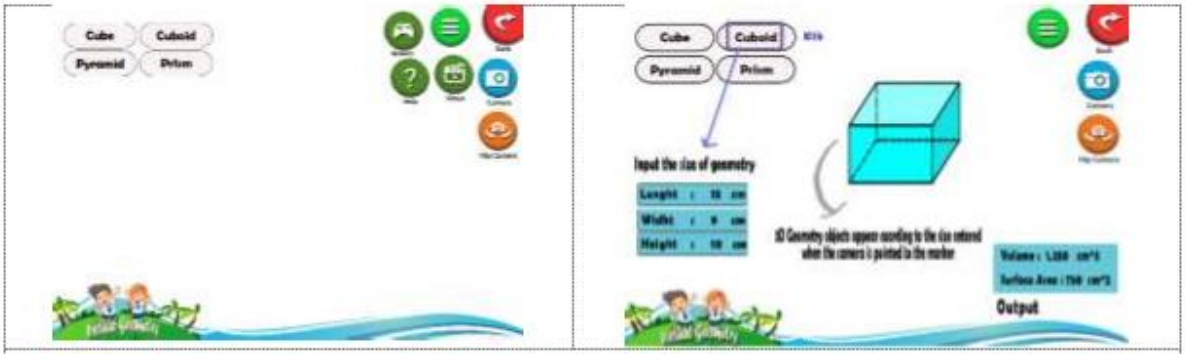

Figure 3
AR output in the form of Visualizing application

Figure 2a is an example of the output of a Visualizing module that has been developed by Auliya & Munasiah (2019). The image is a display of a geometric model using a QR code as a marker regarding the content in it additional modules.

Figure 2b is an example of the output of the Visualizing application which has been developed by Syafril et al. (2021). it is a display of the VirGo application developed by them.

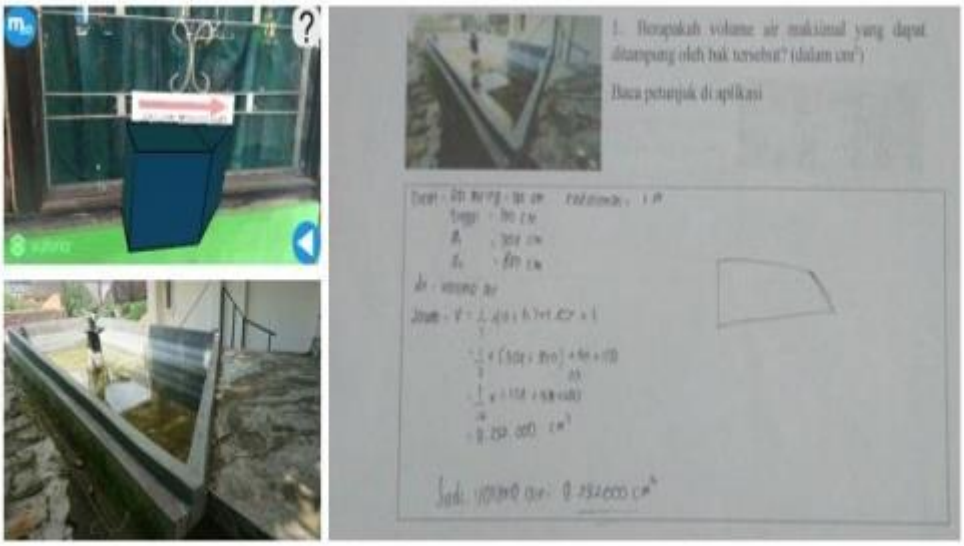

Figure 4
AR output in worksheet form

Figure 3 is an example of the output of a worksheet that has been developed by Ahsan & Cahyono (2020). The image shows a running application combined with an example of an outdoor assignment in the form of a worksheet.

Thomas P. Caudell introduced the AR concept in 1990 in his article "The Term Augmented Reality". Explain the three characteristics of technology that uses the AR concept: a) Able to combine real and virtual environments, b) Can display interactive and direct information, c) Displays in 3D form. Azuma (1997) also explains that the characteristics of AR: combines real and virtual, interactive in real time, registered in 3D. The research studies discussed in the articles consistently fulfill the three main characteristics of Augmented Reality (AR). Firstly, the merging of the real world and the virtual world is reflected in the use of AR to provide more intuitive mathematical visualizations. Secondly, real-time interactivity is emphasized through the development of applications and the use of AR on tablets in various mathematical learning contexts. Thirdly, representation in three dimensions is implemented through the use of AR technology to create a more immersive learning experience. Therefore, these research studies positively contribute to the development of mathematics education by leveraging the advantages of Augmented Reality. Consistent implementation with the key characteristics of AR is expected to enhance students' understanding of mathematical concepts, create more engaging learning experiences, and help overcome barriers in comprehending complex concepts. As a result, these articles serve as valuable sources of knowledge for improving the understanding and application of AR in the context of mathematics education

These articles use various development tools to apply Augmented Reality (AR) technology in the context of mathematics learning. Unity 3D and Vuforia stand out, being used in several articles, demonstrating their flexibility and effectiveness in AR application development. Blender and SketchUp were also used, although in a smaller number of articles, indicating diversity in tool selection based on specific needs. The inclusion of other tools, such as VRSoft GmbH (senselab.io), further illustrates the exploration of different technologies in AR development. The selection of development tools is key in determining the features, interactivity, and overall quality of the AR applications discussed in these articles. Unity 3D with its wide use and support is the main choice. The advantages of Unity 3D are expressed as “3D models adhere well to target images, 3D models work in a flexible way and are compatible with AR add-ons, separate target images of all activities can be worked on via one apk file, and internet connection is not required during the activity . Vuforia also gets special mention for its capabilities in marker-based AR. Blender and SketchUp contribute to the creation of 3D models, improving the visual representation of mathematical concepts. In conclusion, the use of a variety of development tools in these articles represents a comprehensive exploration of the technologies available to enhance the educational aspects of AR applications in the field of mathematics. Tool selection is often tailored to the specific needs and goals of each study, reflecting the flexibility of AR development in educational settings.

The use of Augmented Reality (AR) technology in mathematics learning brings a number of significant benefits. AR not only helps visualize geometric objects (Auliya & Munasiah, 2019), but also contributes to the development of space visualization skills, especially in calculus courses (Herrera et al., 2019; Adrian et al., 2020). Furthermore, the application of AR in mathematics learning has been proven to increase the efficiency and effectiveness of the learning process, overcoming the challenges of understanding complex mathematical concepts (Auliya & Munasiah, 2019; Mantri, 2019; Cao & Liu, 2019; Pritami & Muhimmah, 2018; Ahsan & Cahyono, 2020; Syafril et al., 2021). This approach also succeeded in attracting students' interest and deepening understanding of mathematics material (Auliya & Munasiah, 2019; Rebollo et al., 2022, Syafril et al., 2021, Adrian et al., 2020; Sari et al., 2023; Schutera et al., 2021). Increase self-efficacy (Cai et al., 2019) and Helping mathematical illustrations to solve real problems (Ahsan & Cahyono, 2020, Kang

et al., 2020). The integration of multimedia elements such as text, images, video, animation and sound through AR provides a more memorable learning experience. Additionally, AR helps improve students' spatial abilities through intuitive interaction with 3D objects (Cao & Liu, 2019). AR technology can also be an effective alternative in overcoming the negative impacts of using gadgets in mathematics learning (Pritami & Muhimmah, 2018). With the integration of AR, mathematics learning not only becomes more interactive but also flexible (Darmawan & Jainuddin, 2021; Adrian et al., 2020). AR provides valuable support for STEM learning (Langer et al., 2021), connecting mathematical concepts with their applications in science and technology. Moreover, AR technology not only creates interesting learning but also provides motivation through a play approach (Mantri, 2019; Pritami & Muhimmah, 2018; Rebollo et al., 2022). Thus, AR is emerging as an innovative and comprehensive tool in shaping better mathematics learning experiences.

It can be seen that the main focus of AR studies is on geometric material in general and specifically on geometric shapes. Geometry is a mathematics subject that requires students to visualize (Johar, 2021). Content in mathematics education can often only be conveyed in a very abstract way due to the limited visualization possibilities of classical teaching methods such as blackboard lessons (Schutera, et. al., 2021). So with AR technology, it can be very useful to help visualize vectors and 3D geometry. Visual thinking can make it easier for students to understand complex problems, simplify problems, know the relationship between related problems, as a substitute for calculations, can be a bridge from verbal abstracts to clearer or more concrete forms, helping to clarify what is seen from the problem in accordance with what is thought (Juandi, 2020). Many technological tools, in this case ICT in general, are currently available to integrate information such as magazines, e-books, articles and digital libraries to support student learning processes and improve students' basic mathematics skills.

CONCLUSION AND IMPLICATION

This study delves into the utilization of Augmented Reality (AR) technology in mathematics education, discussing the forms of AR media output, design, commonly used developer tools, benefits of AR, and the common mathematics topics frequently employing AR technology. From the analysis of 15 articles, it is evident that application/games, application/module visualizations, and worksheets are common forms of AR output widely utilized in mathematics learning. The development of AR applications is supported by various developer tools such as Unity 3D, Vuforia, Blender, and SketchUp, providing flexibility and effectiveness in AR application development. This research makes a positive contribution to the development of mathematics education by harnessing the advantages of AR, such as more intuitive mathematical visualizations, engaging learning experiences, and enhanced understanding of complex mathematical concepts. Consistent implementation with the key characteristics of AR is expected to improve students' understanding, create more engaging learning experiences, and overcome barriers in comprehending complex concepts.

In further research, it is hoped to explore more extensively the utilization of Augmented Reality (AR) technology in various mathematical topics beyond geometry. Focusing on the integration of AR in other mathematical topics can provide deeper insights into the potential applications of this technology in comprehensive mathematics learning. Additionally, it is recommended to delve into a better understanding of the additional benefits derived from the use of AR technology in the context of mathematics education. This approach should consider the specific needs and objectives of each research to ensure that the integration of AR technology brings positive and relevant impacts to the mathematics learning experience.

Disclosure statement

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