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Implementation of Augmented Reality in Mathematics Learning on Mathematical Spatial Ability

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Abstract: *Mathematics learning requires the support of effective instructional media and technology to enhance students' mathematical spatial abilities. Augmented Reality (AR) has emerged as a promising technology for facilitating spatial learning, particularly in geometry-related topics. This systematic literature review aims to analyze research trends and the implementation of AR in mathematics learning with respect to mathematical spatial abilities, providing insights for future research and instructional design. The review employed the Systematic Literature Review (SLR) method, initially identifying 900 studies, of which 9 articles published between 2020 and 2025 met the inclusion and exclusion criteria. The findings reveal four major clusters of interconnected research themes, with mathematical spatial ability showing strong associations with spatial visualization, mental rotation, and spatial orientation. The analysis indicates an increasing research trend in recent years, highlighting AR's role not only as a visualization medium but also as an effective pedagogical tool that supports the development of mathematical spatial abilities through interactive three-dimensional representations. These results suggest that AR-based learning has significant potential to enhance spatial understanding in mathematics education.*
Keywords*: augmented reality, mathematical spatial ability*

Abstrak: Pembelajaran matematika memerlukan dukungan media dan teknologi pembelajaran yang efektif untuk meningkatkan kemampuan spasial matematis siswa. Augmented Reality (AR) telah muncul sebagai teknologi yang menjanjikan dalam memfasilitasi pembelajaran spasial, khususnya pada materi yang berkaitan dengan geometri. Tinjauan literatur sistematis ini bertujuan untuk menganalisis tren penelitian serta implementasi AR dalam pembelajaran matematika terhadap kemampuan spasial matematis, sehingga dapat memberikan wawasan bagi penelitian dan perancangan pembelajaran selanjutnya. Penelitian ini menggunakan metode *Systematic Literature Review* (SLR) dengan hasil penelusuran awal sebanyak 900 artikel, kemudian berdasarkan kriteria inklusi dan eksklusi, dipilih 9 literatur yang diterbitkan sejak tahun 2020-2025. Temuan penelitian menunjukkan adanya empat klaster utama tema penelitian yang saling berkaitan, dengan kemampuan spasial matematis memiliki keterkaitan yang kuat dengan visualisasi spasial, rotasi mental, dan orientasi spasial. Hasil analisis menunjukkan adanya peningkatan tren penelitian dalam beberapa tahun terakhir, yang menegaskan peran AR tidak hanya sebagai media visualisasi, tetapi juga sebagai alat pedagogis yang efektif dalam mendukung pengembangan kemampuan spasial matematis melalui representasi tiga dimensi yang interaktif. Temuan ini mengindikasikan bahwa pembelajaran berbasis AR memiliki potensi yang signifikan dalam meningkatkan pemahaman spasial dalam pendidikan matematika.
Kata Kunci: *augmented reality*, kemampuan spasial matematis

INTRODUCTION

The era of society 5.0 emphasizes the integration of technology and artificial intelligence in human life. Mathematics is one of the fundamental disciplines that plays a crucial role in supporting the development of science and technology. Permendiknas No. 21 of 2016 states that there are four important aspects in mathematics, namely numbers, algebra, geometry, and statistics. According to the National Council of Teachers of Mathematics NCTM (2000), geometry plays an important role in the school mathematics curriculum. Fauzi & Arisetyawan (2020) explain that learning geometry makes students think critically and helps them solve everyday problems related to properties, relationships, and elements. However, empirical evidence indicates that students' learning outcomes in geometry, particularly in flat-sided solid figures, remain relatively low. Rhilmanidar et al., (2020) argues that student learning outcomes in flat-sided spatial figures are still low. Students are not yet able to solve problems correctly, especially in identifying spatial figure elements such as space diagonals, plane diagonals, and diagonal planes. Spatial ability is closely related to the field of geometry. Hodiyanto (2018) states that one of the abilities closely related to geometry is spatial ability. Spatial ability is the ability to represent, transform, and visualize the shapes of solid figures (Sirri et al., 2021). There are five indicators of spatial ability according to (Maier, 1998), namely (1) spatial orientation, (2) spatial visualization, (3) spatial relation, (4) spatial perception, and (5) mental rotation. Trisnowali & Alimuddin (2020) spatial ability requires high-level thinking skills in observing the spatial world and imagining geometric shapes because it requires a high level of imagination. If spatial visualization skills are not developed, students will have difficulty learning geometry (Rizkiana et al., 2019).

In reality, students' spatial abilities are still not optimal. Large-scale assessments further confirm this issue. According to the results of PISA (Programme for International Student Assessment) in 2022, there was a decline in mathematics scores, which only reached 366 out of a maximum score of 575, with questions on spatial content and shapes. Meanwhile, the results of the 2015 TIMSS (Trends in International Mathematics and Science Study) survey showed that Indonesian students had low achievements in the areas of mathematical content and cognitive domains. The low spatial abilities of students were also evident in Ningsih (2020) research, which stated that students still had difficulty in constructing perceptions, visualizing, mentally rotating, connecting, and orienting objects.

To address these challenges, innovative learning media that facilitate conceptual understanding of three-dimensional objects are required. One innovation in geometry learning to improve students' mathematical spatial abilities is the use of media or technology that can facilitate students in conceptual discovery of spatial figures. One relevant technology is Augmented Reality (AR). The research conducted by Arifin et al., (2020) which states that AR technology can support spatial abilities in the learning process, especially in spatial geometry material. Sara & Danawak (2021) also stated that the use of AR media in learning spatial figures can improve contextual understanding and students' abilities, especially spatial abilities. Based on the background description, this study aims to analyze research trends from existing empirical research and the implementation of AR in mathematics learning with respect to mathematical spatial abilities, providing insights for future research and instructional design.

METHOD

This study used the Systematic Literature Review (SLR) method. Systematic Literature Review is a method used to determine, evaluate, and interpret all findings of research problems in answering questions that have been found (Rachmawati et al., 2021)

The SLR method procedure used in this study follows the steps outlined by Triandini et al., (2019) as shown in Figure 1.

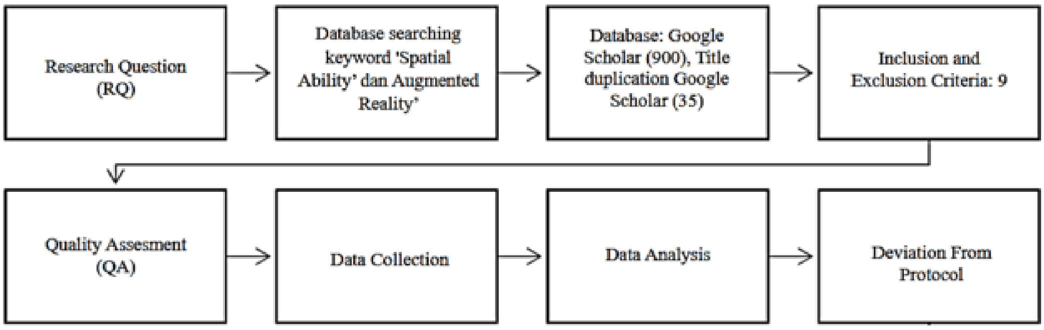

Figure 1. Systematic Literature Review Steps

The first step is to determine the Research Question based on the needs of the selected topic. In this study, the Research Questions (RQ) include (RQ1) What are the research trends from 2020 to 2025 related to the implementation of AR in mathematics learning on spatial abilities?; (RQ2) How does the implementation of AR in mathematics learning affect spatial abilities?

The second step is the Search Process. Literature searches were conducted using the Crossref, Google Scholar, and Semantic Scholar databases assisted by the Publish or Perish application in the range of years 2020-2025. The primary search keyword "Augmented Reality" and “Spatial Ability” to answer the research objectives on the implementation of Augmented Reality on mathematics education to the development of spatial ability from the trend of research conducted in the last six years is observable.

The third step is to determine the inclusion and exclusion criteria. A selection was made from the 900 titles obtained based on inclusion and exclusion criteria that began with the title, abstract, and duplication of titles from the three databases. At this stage, a decision is made as to whether the data found is suitable for use in SLR research or not. The inclusion and exclusion criteria used in this study can be seen in Table 1.

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Literature relevant to the topic of AR media implementation in mathematics learning on mathematical spatial ability	Literature not relevant to the topic of AR media implementation in mathematics learning on mathematical spatial abilities
Research literature is taken from national or international journals that are indexed	Research literature does not come from national or international journals that are indexed
Literature published between 2020 and 2025	Literature published between 2020 and 2025
Literature obtained from Crossref, Google Scholar, and Semantic Scholar	Literature obtained from Crossref, Google Scholar, and Semantic Scholar
Literature containing the research subject of students	Literature not containing the research subject of students

The fourth step is Quality Assessment (QA). This step is carried out to evaluate the literature obtained based on QA criteria. In this study, the QA criteria determined include: (QA1) Does the literature discuss the implementation of AR in mathematics learning on mathematical spatial abilities? (QA2) Is the literature a journal article or national or international that have been indexed?; (QA3) Was the literature published between 2020 and 2025?; (QA4) Was the literature obtained from Crossref, Google Scholar, and Semantic Scholar?; (QA5) Were the research participants students? With the QA criteria established, literature that met all QA criteria was considered suitable as a reference for this study. The QA process was carried out systematically, and only studies that met all QA criteria were included in the final analysis.

The fifth step was Data Collection. In this step, the researcher collects the literature to be used in the research based on the determined QA. Key information, including author, year, research focus, methodology, AR implementation, and reported impacts on spatial abilities, was recorded in a structured database to ensure completeness and reliability.

The sixth step is Data Analysis. After obtaining the literature, the next step is to analyze the data obtained to answer the established RQ. Relevant data were extracted, coded, and grouped based on the identification of major research trends, effective AR implementation strategies, and the most influential aspects of spatial abilities. Further keyword analysis and clustering clarified the relationships among themes and trends during the 2020-2025 period, providing a comprehensive understanding of AR’s role in enhancing students’ mathematical spatial abilities.

The seventh step is Deviation from Protocol. Correcting word equivalents to be adjusted based on keywords in the database to ensure consistency during data analysis and synthesis. Through this systematic process, the selected literature was comprehensively analyzed to provide an in-depth understanding of research trends and the pedagogical role of AR in enhancing students’ mathematical spatial abilities.

RESULT AND DISCUSSION

The results of the literature search using the Publish or Perish application through the Google Scholar database in the 2020-2025 period with the keywords used in the search were “Spatial Ability” and “Augmented Reality”. A total of 900 pieces of literature were found, which were then filtered using inclusion and exclusion criteria, resulting in 34 pieces of literature. The literature that met the inclusion criteria was evaluated using Quality Assessment criteria. Nine pieces of literature passed QA, consisting of two internationally indexed pieces of literature and seven nationally indexed pieces of literature indexed by Sinta. After that, the researcher reviewed the nine pieces of literature and found answers to the Research Question that had been formulated. The literature data results were collected and presented in Table 2.

Table 2. Selected Literature Research Results

Literature Code	Researcher, Year	Journal	Indexing	Research Result
L01	(Velázquezet & Mendez, 2021)	MDPI	Scopus, Web of Science (WOS)	The results of the study indicate that the use of Geogebra AR in teaching mathematical functions has a significant effect on improving student learning outcomes and spatial intelligence compared to

Literature Code	Researcher, Year	Journal	Indexing	Research Result
				conventional teaching methods. AR is effective in STEM education, especially mathematics, where spatial abilities are key. In addition, Geogebra AR has been proven to be easy for students to operate.
L02	(Nurwijaya, 2022)	Jurnal Ilmiah Pendidikan Matematika	Sinta 3	The results of this study indicate that there is an effect of the augmented reality-assisted problem-based learning model on students' spatial abilities.
L03	(Yanuarto & Iqbal, 2022)	Edumatica: Jurnal Pendidikan Matematika	Sinta 2	The results of this study indicate that AR learning media can improve mathematical spatial abilities.
L04	(Subhi et al., 2023)	Jurnal Penelitian Pembelajaran Matematika Sekolah	Sinta 5	The results of this study indicate that students who use GO-AR learning media show an improvement in spatial reasoning skills that is better than students who do not use GO-AR learning media.
L05	(Lutfi et al., 2024)	Social, Humanities, and Educational Studies	Sinta 4	The results of this study indicate that there is a significant difference in student learning outcomes on the pretest and posttest after they used AR Geogebra media in spatial geometry material. AR Geogebra technology can help students recognize spatial geometry, and AR Geogebra interactive media can be integrated into spatial geometry learning.
L06	(Rahman & Halim, 2024)	Sains Humanika	Crossref & DOAJ	The descriptive analysis results show an increase in the average score for students' spatial reasoning. The inferential analysis results also prove that there is a significant difference in the average score between the pretest and posttest for students' spatial reasoning.
L07	(Munahefi et al., 2024)	Union: Jurnal Ilmiah	Sinta 3	The results of the study show that the developed

Literature Code	Researcher, Year	Journal	Indexing	Research Result
		Pendidikan Matematika		application obtained very feasible criteria from experts and very practical criteria from practitioners. The test results also show an average increase in student learning outcomes of 667%. The ACITYA application is declared to be very feasible, very practical, and capable of improving students' spatial abilities.
L08	(Ani D.I., & Refliani, 2025)	Prima: Jurnal Pendidikan Matematika	Sinta 3	The results show that the average student score increased and the use of augmented reality had a significant effect on students' spatial visualization abilities. A total of 91% of students also responded positively to augmented reality-based learning.
L09	(Basir, M.A., 2025)	Jurnal Pendidikan Matematika Malikussaleh	Sinta 4	The results of this study indicate that the integration of AR technology in spatial learning is effective in improving spatial abilities, especially when tailored to students' cognitive styles.

(RQ1) What Are the Research Trends in 2020-2025 Regarding the Implementation of AR Media in Mathematics Learning on Mathematical Spatial Abilities?

The research trends related to the implementation of AR media in mathematics learning on mathematical spatial abilities in 2020-2025 are as follows.

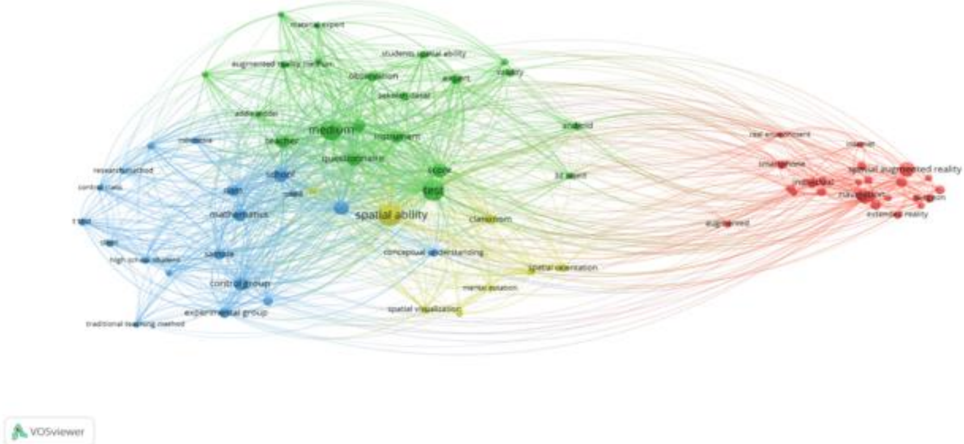

Figure 2. Visualization of the Relationship Between Keywords

Based on Figure 2, there are four different colors. These color differences indicate four clusters in the data. Circles of varying sizes indicate the number of discussions on that keyword, with larger circles indicating more discussions. Meanwhile, the connecting lines between the circles illustrate the relationship between one keyword and another.

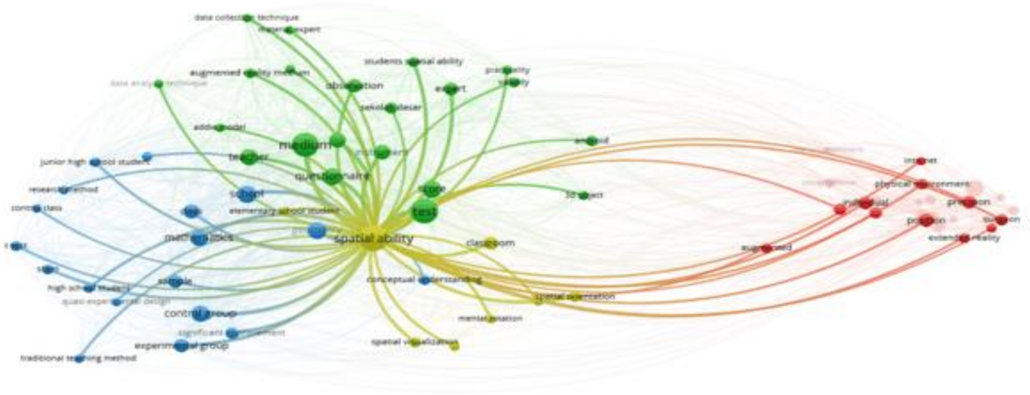

Figure 3. The Relationship Between of "Spatial Ability" with Other Keywords

Figure 3 shows that the keyword "spatial ability" belongs to cluster 4 with 58 links and 111 events. Keywords strongly related to "spatial ability" are spatial visualization, mental rotation, and spatial orientation. These keywords are directly related to other keywords in three different clusters, namely those in cluster red, blue, and green. This may indicate that, from the studies conducted, the keywords in these clusters are most likely to be topics in single research titles.

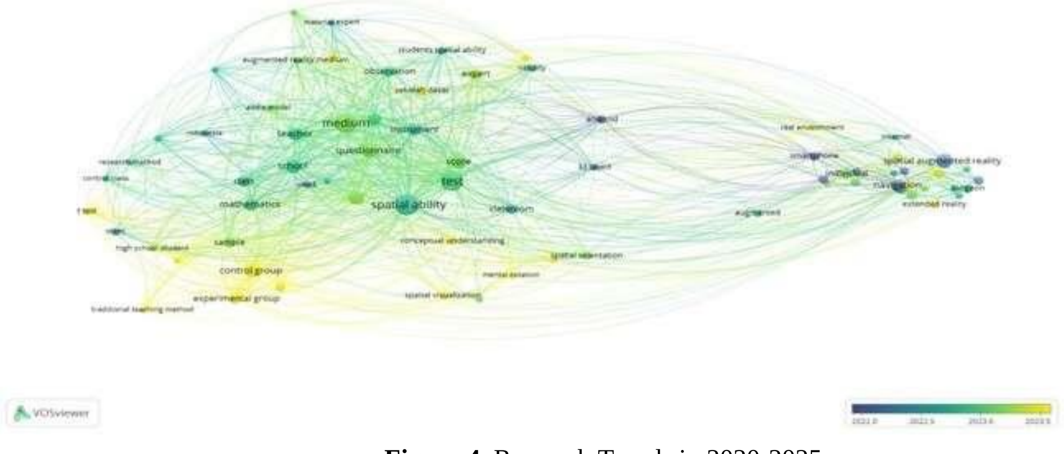

Figure 4. Research Trends in 2020-2025

Figure 4 shows that research trends on the implementation of AR media in mathematics learning on mathematical spatial abilities studied from 2020 to 2025 are distinguished by color. Brighter colors indicate newer research, while darker colors indicate older publications. The topics discussed in the research reflect the development of trends in studies related to the implementation of AR media on mathematical spatial abilities during that period. Thus, the development of research related to the implementation of AR media on mathematical spatial abilities over time can be monitored and understood.

(RQ2) How Does the Implementation of AR Media in Mathematics Learning Affect Students' Mathematical Spatial Abilities?

An analysis of nine selected literature on the implementation of Augmented Reality (AR) in mathematics learning on spatial abilities was conducted based on several main aspects, namely the level of education, the learning model or approach used, the teaching material studied, and the software and hardware that support AR implementation. The results of the classification of the nine literature sources are presented in the following table to provide an overview of the trends in research that has been conducted at various educational levels in the context of AR-based mathematics learning.

Table 3. Classification of Research

Literature Code	Educational Level	Learning Model	Material	Software/Hardware Used
L01	Secondary Education	-	Function	GeoGebra
L02	SMA	Problem Based Learning	Geometry	Andorid
L03	Junior High School	-	Geometry	Android
L04	Junior High School	Blended Discovery Learning	Curved Solids	Android
L05	Elementary School	-	3D Shapes	GeoGebra
L06	Junior High School	Inquiry Based Learnin	3D Shapes	Android
L07	Junior High School	Problem Based E-Learning	Polyhedra	E-Learning
L08	Junior High School	-	3D Shapes	Android
L09	Junior High School	Kognitive Approach	3D Shapes	Android

Education Levels

Based on the analysis of nine pieces of literature, it appears that education levels were used as the subject of the research. Of the nine pieces of literature analyzed, six focused on junior high school, one on senior high school, one on elementary school, and one on secondary education equivalent to junior high school or early senior high school. The subject of research at the junior high school level tends to be used more in studies on the implementation of AR in mathematics learning on mathematical spatial abilities in the 2020-2025 period. The dominance of research at the junior high school level shows that the early adolescent age group is the main focus in the development and application of AR-based learning media, especially for geometry material that requires high spatial visualization abilities.

These findings are in line with several previous studies showing that junior high school students (aged 12-15 years) are still in the early formal operational stage of development according to Piaget's theory, where students are capable of thinking logically about abstract objects but still need concrete visual representations to understand three-dimensional concepts. Therefore, the use of AR is very relevant because this technology is able to bridge the transition from concrete to abstract representations through interactive visualization and manipulation of virtual objects (Nurwijaya, 2022) Meanwhile, at the elementary school level, research on the implementation of AR is still relatively limited. A study conducted by Lutfi & Kusumastuti (2024) shows that the use of AR in elementary school students can increase learning interest and understanding of basic spatial concepts, but its effectiveness still depends on the level of technological readiness and teacher assistance. Meanwhile, at the high school level, research such as that conducted by Basir (2025) shows that AR can improve students' mathematical spatial abilities, although its implementation requires more complex instructional design adaptations.

Based on these trends, it can be concluded that junior high school is the most ideal level for the application of AR in mathematics learning for mathematical spatial abilities. This is because at this level, students are in a phase of cognitive development that requires interactive and dynamic visual media to conceptualize the relationships between geometric elements. Thus, current research confirms that the use of AR at the junior high school level is a strategic focus in developing mathematics learning that is more contextual, interactive, and in line with the characteristics of students' cognitive development, as well as supporting the achievement of 21st-century learning objectives that emphasize spatial thinking, creativity, and problem-solving skills.

Learning Models

Based on the analysis of nine pieces of literature, it was found that the variety of learning models and approaches used in the implementation of AR in mathematics learning on spatial abilities showed diverse trends in accordance with the objectives and context of the research. Based on all the literature, one used the Problem Based Learning (PBL) model, one used Blended Discovery Learning, one applied Inquiry Based Learning (IBL), one used Problem-Based E-Learning, one applied a cognitive style approach, and three others did not explicitly mention the learning model. The dominance of problem-based and discovery-based models indicates that AR is most effective when combined with a constructivist approach, which places students at the center of learning activities and encourages independent exploration of mathematical concepts. Models such as PBL and IBL enable students to actively engage in problem solving, visual exploration, and hypothesis testing through spatial representations presented by AR technology, there by significantly supporting the development of spatial abilities.

Problem-Based Learning and Blended Discovery Learning models stand out in their ability to connect AR with real-world learning contexts. In PBL, AR serves to strengthen spatial understanding by presenting three-dimensional visualizations that help students analyze and solve space-based problems, as evidenced by research that found a significant improvement in students' spatial representation. Meanwhile, in Blended Discovery Learning and Inquiry-Based Learning, AR is used to encourage investigation and discovery of concepts through direct interaction with virtual objects, reinforcing learning through visual and kinesthetic experiences. The Problem-Based E-learning model extends these benefits in a digital environment, enabling remote collaboration with the support of interactive simulations. Research using a cognitive style approach highlights that the effectiveness of AR is also influenced by individual students' characteristics in processing spatial information. Although the three pieces of literature do not mention specific models, all studies show an improvement in spatial abilities, confirming that the use of AR inherently enhances geometric understanding and spatial relations, even without the support of specific learning models.

Materials Used in Research

Based on the analysis results, it can be seen that the variety of materials used in research on the implementation of AR in mathematics learning on spatial abilities includes one study on functions, two on geometry, four on solid figures, one on curved-sided solid figures, and one on flat-sided solid figures. The dominance of research on solid figures shows that this topic is most relevant to the application of AR because it requires high spatial visualization and representation skills. The use of AR in geometry and solid geometry learning has been proven to help students visualize three-dimensional shapes, understand the relationships between spatial elements, and improve mental rotation and spatial perception skills. In the context of polyhedra, AR allows students to connect two-dimensional representations with real three-dimensional shapes, while in curved solids, such as cylinders, cones, and spheres, AR effectively shows the relationship between surface area and volume dynamically. Although only one study discussed function material, the results showed that AR also has potential in visualizing three-dimensional function graphs and deepening understanding of the relationship between variables. Overall, the trend of research focusing on geometry and spatial figures reinforces the evidence that AR is an effective medium for developing students' mathematical spatial abilities, as it provides a concrete, interactive, and contextual learning experience.

Software/Hardware Used

Based on the analysis of nine pieces of literature, the variety of software and hardware used in the implementation of AR in mathematics learning for spatial abilities shows a strong tendency toward the use of mobile devices and android-based applications. Based on all the literature, two used GeoGebra AR, six literature used Android applications, and one used an AR-integrated e-learning platform. The dominance of android applications indicates the high accessibility and flexibility of this technology in supporting interactive learning, where students can directly manipulate three-dimensional objects using their phone's camera and sensors to strengthen their spatial visualization skills (Nurwijaya, 2022; Yanuarto & Iqbal, 2022; Subhi et al., 2023; Basir, 2025). Meanwhile, the use of GeoGebra AR has proven effective in displaying function graphs and three-dimensional geometric objects in real time, thereby helping students understand spatial relationships and mental rotation without relying on manual calculations (Del Cerro Velázquez & Méndez, 2021; Lutfi & Kusumastuti, 2024) AR-based e-learning platforms, such as those developed by Lutfi & Kusumastuti (2024), offer distance learning opportunities that enable independent exploration of mathematical objects through a browser or LMS. Overall, the use of a combination of interactive software and easily accessible mobile hardware plays an important role in increasing the effectiveness of AR-based learning, strengthening spatial understanding, and encouraging active student engagement in contextual and adaptive mathematics learning in the 21st century.

The Influence and Effectiveness of AR on Mathematical Spatial Ability

A literature review of nine studies shows that the implementation of AR in mathematics learning has a positive effect on improving students' mathematical spatial ability. AR functions not only as a visual aid, but also as a pedagogical tool that supports various aspects of learning, from mental representation and reasoning to learning motivation. These findings indicate that AR meets pedagogical needs, namely the ability to represent three-dimensional objects that can be manipulated. However, the success of AR implementation also depends on the synergy between technology, challenging learning tasks, and teachers' pedagogical skills.

The findings of (Del Cerro Velázquez & Méndez, 2021) show that the use of Geogebra AR in teaching mathematical functions has a significant effect on improving student learning outcomes and spatial intelligence compared to conventional teaching. Similar results were also shown by Nurwijaya (2022), who found that the AR-assisted PBL model had an effect on students' spatial abilities. The integration of AR in problem-based learning models has been proven to improve spatial abilities through contextual three-dimensional visualization. This empirical evidence supports the idea that AR is most effective when combined with learning models that require problem solving and meaning construction, namely PBL.

Research by Yanuarto & Iqbal (2022) reinforces that AR-based learning media can significantly improve students' mathematical spatial abilities. This is in line with the findings of Subhi et al., (2023), who used GO-AR media to encourage better spatial reasoning compared to traditional learning. The consistency of these findings reinforces the reliability of the claim of AR's effectiveness.

The use of the Geogebra AR application developed by Lutfi & Kusumastuti (2024) has been proven effective in helping students recognize spatial shapes. This application provides an interactive experience that allows manipulation of three-dimensional objects, making spatial understanding more concrete. These results are reinforced by Abd Rahman & Abd Halim, (2024), who found a significant difference between pretest and posttest results in students' spatial reasoning after using AR media. These findings highlight the importance of the quality of interactivity features in AR applications.

Research by Munahefi et al., (2024) shows that the ACITYA application meets the criteria of being highly feasible and practical based on validation by experts and practitioners. The trial results showed an increase in student learning outcomes of up to 667%, confirming the effectiveness of AR in improving spatial abilities and learning efficiency. Additionally, the results of Indriani (2025) study show that students' average scores increased significantly after using AR-based media, with 91% of students responding positively to AR-based learning. However, expert validation and high student response are strong indicators that the development of AR media is worth considering on a larger scale, provided that it is supported by adequate teacher training and infrastructure.

The research by Basir (2025) adds that the integration of AR technology in spatial learning is effective in improving spatial abilities, especially when tailored to students' cognitive styles. This adjustment reinforces learning differentiation and allows students with different learning profiles to achieve optimal understanding. The results of this study confirm that AR not only plays a role in improving cognitive aspects, but also has a positive impact on students' motivation, engagement, and learning experiences. The use of learning media that can facilitate students visually, auditorily, and interactively, such as AR, has the potential to become a relevant and sustainable pedagogical innovation in mathematics learning, particularly in the development of mathematical spatial abilities in the digital age.

This study provides a comprehensive overview of research trends concerning the implementation of AR in mathematics learning to enhance mathematical spatial ability during the 2020-2025 period. The bibliometric mapping reveals that spatial ability occupies a central position in the research network, as indicated by its high number of links (58) and occurrences (111). Its strong association with sub-components such as spatial visualization, mental rotation, and spatial orientation confirms that contemporary AR-based mathematics research conceptualizes spatial ability as a multidimensional construct rather than a single cognitive skill. This aligns with established spatial cognition frameworks, which emphasize that effective geometry learning requires the integration of multiple spatial processes simultaneously.

The cross-cluster connections observed in the network visualization suggest that studies frequently integrate spatial ability with pedagogical approaches, learning technologies, and specific mathematical contents within a single research design. This pattern indicates a growing tendency toward interdisciplinary and integrative research, where AR is not treated merely as a technological add-on but as an embedded component of instructional design aimed at supporting higher-order spatial reasoning. Furthermore, the overlay visualization demonstrates a clear temporal progression, with recent studies increasingly focusing on learner-centered models, mobile AR platforms, and context-rich mathematical tasks. This trend reflects a broader shift in mathematics education research toward technology-enhanced learning environments that emphasize interactivity, adaptability, and authentic problem solving.

The dominance of junior high school as the primary research context highlights this educational level as a strategic target for AR implementation in mathematics learning. From a developmental perspective, students aged 12–15 are transitioning into the formal operational stage, where abstract reasoning begins to develop but still relies heavily on concrete and visual supports. AR effectively addresses this cognitive need by enabling learners to manipulate three-dimensional representations that bridge concrete experiences and abstract mathematical concepts. Consequently, the prevalence of studies at this level suggests that researchers recognize AR’s potential to scaffold spatial reasoning during a critical phase of cognitive development. In contrast, the limited number of studies at the elementary and senior high school levels indicates potential research gaps. While existing evidence shows that AR can enhance motivation and conceptual understanding among younger learners, its effectiveness remains contingent on technological readiness and instructional guidance. At the senior high school level, the smaller number of studies may reflect the increased complexity of mathematical content, which requires more sophisticated instructional design to ensure that AR supports conceptual understanding rather than causing cognitive overload. These findings suggest that future research should explore age-specific AR design principles to optimize its pedagogical impact across educational levels.

The analysis of learning models reveals a strong alignment between AR implementation and constructivist pedagogical approaches, particularly Problem Based Learning (PBL), Inquiry-Based Learning (IBL), and Discovery Learning. The prominence of problem- and inquiry-oriented models indicates that AR is most effective when learners are actively engaged in exploring, manipulating, and reasoning about spatial objects rather than passively observing visualizations. AR-enhanced environments allow students to test hypotheses, visualize alternative solution paths, and refine their spatial reasoning through iterative interaction with virtual objects. Notably, even studies that did not explicitly specify a learning model reported improvements in spatial ability, suggesting that AR possesses inherent affordances that support spatial learning. However, the strongest learning outcomes were consistently reported when AR was embedded within a well-structured pedagogical framework. This finding reinforces the argument that technology alone does not guarantee learning gains; rather, its effectiveness depends on alignment with instructional strategies that promote cognitive engagement and meaning construction.

The predominance of research on solid geometry and three-dimensional figures further underscores the natural compatibility between AR and spatially demanding mathematical topics. Solid figures require learners to mentally manipulate objects, understand relationships between faces, edges, and vertices, and connect two-dimensional representations with three-dimensional forms. AR addresses these challenges by providing dynamic, manipulable visualizations that externalize spatial transformations, thereby reducing cognitive load and supporting deeper conceptual understanding. Although fewer studies addressed functions and other non-geometric topics, the positive outcomes reported in these contexts suggest that AR holds potential beyond traditional geometry instruction. The ability to visualize three-dimensional graphs and variable relationships dynamically indicates promising avenues for extending AR applications to advanced mathematical concepts that also rely on spatial reasoning.

The strong preference for Android-based applications reflects practical considerations of accessibility, affordability, and ease of implementation. Mobile AR platforms allow students to engage with mathematical objects anytime and anywhere, fostering continuity between formal classroom learning and informal exploration. Meanwhile, tools such as GeoGebra AR demonstrate the value of integrating AR with established mathematical software, enabling precise visualization while maintaining mathematical rigor. The emergence of AR-integrated e-learning platforms further indicates a shift toward flexible and hybrid learning environments. These platforms support independent exploration and remote collaboration, which are increasingly relevant in post-pandemic educational contexts. Collectively, these technological trends suggest that scalability and usability are key factors driving the adoption of AR in mathematics education research.

Across the nine studies reviewed, consistent evidence demonstrates that AR has a positive and significant impact on students' mathematical spatial abilities. AR supports spatial learning not only by enhancing visualization but also by fostering active engagement, motivation, and conceptual reasoning. The strongest effects were observed when AR was combined with problem-based tasks, high-quality interactivity features, and instructional scaffolding tailored to learners' cognitive characteristics. Importantly, several studies highlight that individual differences, such as cognitive style, mediate the effectiveness of AR-based learning. This finding underscores the importance of adaptive AR design that accommodates diverse learner profiles. Moreover, while expert validation and positive student responses indicate high feasibility and acceptance, sustainable implementation requires adequate teacher training, infrastructure, and curriculum alignment.

Overall, the findings confirm that AR represents a pedagogically meaningful innovation in mathematics education. When thoughtfully integrated into instructional design, AR has the potential to enhance mathematical spatial ability, support 21st-century skills, and transform students' learning experiences from abstract and symbolic to interactive and conceptually grounded.

CONCLUSION AND SUGGESTION

Based on the results of the analysis and discussion, it can be concluded that the implementation of AR in mathematics learning shows a growing research trend from year to year and has a positive effect on improving students' mathematical spatial abilities. Bibliometric analysis shows four main clusters with the keyword "spatial ability" as the strongest center of relevance, indicating the dominant role of this topic in AR-related research. The results of the literature review confirm that AR not only functions as a visual aid but also as an effective pedagogical tool in developing mental representation, spatial reasoning, and learning motivation through interactive three-dimensional visualization. The implementation of AR in mathematics learning can increase activity, engagement, and understanding of concepts in a more concrete and contextual manner. Thus, AR has the potential to become a relevant learning innovation in supporting the development of spatial abilities and realizing a more meaningful mathematics learning process in the digital era.

The article offers valuable insights into the role of Augmented Reality (AR) in enhancing students' mathematical spatial abilities, particularly in the context of geometry learning. However, it would benefit from a more in-depth discussion of the practical challenges faced by educators in integrating AR into classroom settings. Furthermore, the study could be strengthened by exploring the long-term effects of AR on both spatial abilities and overall academic performance. A comparative analysis between AR and traditional teaching methods would provide a more nuanced understanding of its effectiveness. Future research could also investigate the potential for integrating AR with other emerging technologies, such as Artificial Intelligence, to further optimize mathematics education.

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