JDIME : Journal of Development and Innovation In Mathematics Education

Volume 3, Number 1, April 2025, pp. 22-34
P-ISSN: 2986-2744 E-ISSN: 2986-402X
Open Access: http://dx.doi.org/10.32939/jdime.v3i1.5070

Innovative Transformation Geometry Learning: Developing Augmented Reality Media to Boost Students' Critical Thinking

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ARTICLE INFO

Article history:
Available online April 05, 2025

Kata Kunci:
Augmented Reality, Geometri, Matematika, Berpikir Kritis, Media Pembelajaran

Keywords:
Augmented Reality, Geometry, Mathematics, Critical Thingking, Media Learning

Abstrak

Penelitian ini bertujuan untuk mengembangkan media pembelajaran geometri transformasi berbasis Augmented Reality (AR) guna meningkatkan pemahaman dan keterampilan berpikir kritis mahasiswa. Metode yang digunakan adalah Penelitian dan Pengembangan (RnD) dengan model pengembangan perangkat lunak waterfall. Model ini dipilih karena sifatnya yang sistematis dan berurutan, yang memudahkan pemetaan tiap tahapan secara jelas. Tahapan pengembangan mencakup perencanaan, desain, konstruksi, pengujian, dan penerapan, dengan melibatkan uji validitas oleh para ahli dan uji coba produk kepada mahasiswa. Hasil validitas menunjukkan bahwa aplikasi AR yang dikembangkan dinilai sangat layak oleh para ahli media dan ahli materi, dengan persentase validitas mencapai 82% dan 83%, masing-masing. Uji coba produk kepada mahasiswa menunjukkan bahwa aplikasi AR praktis digunakan, dengan tingkat ketuntasan belajar mahasiswa mencapai 88,4%. Hasil penelitian ini menunjukkan bahwa media pembelajaran berbasis AR efektif dalam meningkatkan pemahaman konsep geometri transformasi dan keterampilan berpikir kritis mahasiswa. Implikasi dari hasil penelitian ini adalah bahwa penggunaan media pembelajaran berbasis AR dapat diintegrasikan dalam pembelajaran matematika untuk meningkatkan efektivitas pengajaran, khususnya pada materi geometri, serta mendorong pengembangan keterampilan berpikir kritis siswa yang lebih baik.

Abstract

This study aims to develop an Augmented Reality (AR)-based transformation geometry learning media to enhance students' understanding and critical thinking skills. The method used is Research and Development (RnD) with a waterfall software development model. This model is chosen due to its systematic and sequential nature, which facilitates the clear mapping of each development stage. The development stages include planning, design, construction, testing, and implementation, involving validity testing by experts and product trials with students. The validity results show that the developed AR application is deemed highly feasible by media and subject matter experts, with validity percentages reaching 82% and 83%, respectively. Product trials with students showed that the AR application is practical to use, with a student learning completion rate of 88.4%. The results of this study indicate that AR-based learning media is effective in improving students' understanding of transformation geometry concepts and enhancing their critical thinking skills. The implication of this research is that AR-based learning media can be integrated into mathematics teaching, particularly for geometry topics, to improve teaching effectiveness and foster the development of better critical thinking skills in students.

INTRODUCTION

Mathematics education, particularly in geometry, often faces challenges related to the understanding of concepts and the application of theories in real-world contexts. One topic frequently considered difficult by students is transformation geometry, which involves concepts such as rotation, reflection, translation, and dilation (Handayani, 2017; Lestari & Suryani, 2019). This difficulty arises from the abstract nature of these concepts, which often hinders students' ability to visualize and comprehend them. Therefore, innovative approaches are needed to facilitate students' understanding of this material. One promising technology for enhancing

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geometry learning is Augmented Reality (AR), which can visually present geometric concepts in an interactive and dynamic way (Azuma, 2017; Haryono, 2018).

Augmented Reality (AR), as a technology that combines the real world with the virtual world, holds significant potential for enhancing the understanding of mathematical concepts, particularly in geometry. Through AR, students can view geometric objects in three-dimensional form, which can be rotated, altered, or manipulated directly—activities that are not possible with conventional media such as textbooks or whiteboards (Mohamad et al., 2020; Pramudito & Ariyanto, 2020). Thus, AR can facilitate a more interactive and engaging learning experience for students, reducing boredom and enhancing their motivation to learn. Furthermore, AR can introduce abstract concepts in a more concrete and visual manner, enabling students to understand and apply theories more easily (Hendrawan et al., 2021; Rahman et al., 2019).

One important aspect of mathematics education is the development of students' critical thinking skills. Critical thinking in mathematics involves the ability to analyze, evaluate, and solve problems in a logical and structured manner (Sagala & Purnomo, 2019). Previous research has shown that technology-based learning, such as AR, can support the development of critical thinking skills, as this technology allows students to interact with learning materials in a more active and creative way (Gholami & Sheybani, 2019; Mulyana et al., 2020). In the context of transformation geometry learning, AR can assist students in identifying and solving problems in a more in-depth manner, thereby enhancing their critical thinking skills (Sudirman & Firdaus, 2020).

With the advancement of technology, the use of AR in education has become an increasingly popular research topic across various disciplines, including mathematics education. Studies on the use of AR in teaching transformation geometry have shown that this technology not only improves students' understanding of geometric concepts but also motivates them to engage more actively in learning activities (Ferdiani & Gunawan, 2018; Fauzan & Yusuf, 2021). However, despite the effectiveness of AR in several studies, its implementation in the context of transformation geometry education in Indonesia remains limited. This indicates a need for further research on the development of more effective AR-based learning media that is suitable for the educational context in Indonesia (Lutfiana et al., 2021; Suryani & Pratiwi, 2020).

Augmented Reality (AR), as an interactive technology, has rapidly developed across various sectors, including education, and is widely used to enhance the learning process, particularly in mathematics education. In the context of geometry learning, AR provides a dynamic visual experience that allows students to view and interact with mathematical objects in three dimensions (3D), which is extremely helpful for understanding abstract concepts that are difficult to grasp through conventional methods (Gürbüz & Yıldırım, 2016; Yoon & Jeong, 2020). In recent years, AR has been applied to various mathematics learning topics, including algebra, geometry, and statistics, to increase student engagement and strengthen their understanding of the material (Wojciechowski & Cellary, 2013; Baki et al., 2017).

According to Chao et al. (2020), AR enables clearer visualization of geometric objects, such as shape transformations, helping students visualize and understand the relationships between geometric objects in three-dimensional space. For example, in learning geometric transformations such as translation, rotation, reflection, and dilation, AR can be used to display these objects in an interactive space, allowing students to directly observe and modify the position and orientation of objects according to the transformation commands given. This makes it easier for students to understand how each transformation affects the shape and position of the object more concretely than relying solely on two-dimensional representations in textbooks (Kynigos & Spyrou, 2018; Glover et al., 2014).

Research by López et al. (2019) shows that the use of AR in geometry learning can enhance students' understanding of basic geometric concepts and reduce the difficulty in understanding abstract topics such as geometric transformations. AR also helps students understand the connection between two-dimensional and three-dimensional geometry, which is crucial for developing their understanding of space and shapes. This can improve students' problem-solving skills, an essential component of developing their critical thinking abilities (Chin & Berge, 2020;

Pérez-Marín et al., 2017). Additionally, AR allows for personalized learning, as students can progress at their own pace and select geometric objects for further study.

One of the major advantages of using Augmented Reality (AR) in mathematics education is that it promotes active and exploratory learning. According to Radu (2014), AR allows students to interact with learning content directly and more deeply, which has the potential to increase their motivation to learn. AR-based learning can also enrich the learning experience through more immersive simulations, enabling students to not only listen to theoretical concepts but also to experience them firsthand (Bacca et al., 2014). By combining elements of the real and virtual worlds, AR gives students the opportunity to observe the results of mathematical experiments in real-time, providing a better understanding of the concepts being studied (Akçayir & Akçayir, 2017; Brinson, 2018). However, despite the many potentials of AR in mathematics education, there are some challenges in its implementation in schools. One of the main challenges is the limitation of resources and infrastructure in many schools, particularly in developing countries (Cai et al., 2020; Jin et al., 2021). Many schools lack adequate hardware, such as tablets or smartphones, which are necessary to run AR applications. Additionally, the lack of training for teachers in using AR is also a barrier to integrating this technology into the classroom. Therefore, to fully harness the potential of AR in geometry learning, a comprehensive approach is needed, which involves the development of suitable learning materials, teacher training, and improved access to technological devices (Sari et al., 2019; Bozkurt & Akin, 2018).

Critical thinking skills are the ability to analyze and evaluate information objectively and draw rational conclusions. In the context of mathematics education, critical thinking is crucial as students are expected to solve problems that require not only the correct mathematical procedures but also deep analysis and reasoning (Ramsden, 2003; Ku, 2009). The development of these skills is one of the main goals of mathematics education at the secondary school level (Adams, 2015; Perkes & Klapwijk, 2017). Research by Hidayati et al. (2018) and Rahmawati & Hidayat (2021) shows that the use of technology that allows students to interact directly with learning materials can enhance their critical thinking skills. In the context of AR, direct interaction with manipulable geometric objects gives students the opportunity to think about the effects of various geometric transformations on those objects. This encourages students to think more critically about the relationships between the concepts they are learning and how these concepts can be applied in broader situations (Prasetyo et al., 2019; Hasyim & Syafi'i, 2020).

A study by Zaki et al. (2019) also highlights the importance of technologies like AR in enhancing critical thinking skills in mathematics education. In their experiment, students who used an AR application to learn about transformation geometry showed significant improvements in their critical thinking skills compared to students who used traditional learning methods. One reason AR can enhance critical thinking is because it allows students to explore various possibilities and solutions through simulations and experiments, encouraging them to question and evaluate the results they obtain (Wu et al., 2013; Taylor et al., 2015). However, despite the great potential of AR to enhance critical reasoning, research also suggests that AR implementation must be accompanied by appropriate pedagogical approaches. Using AR solely based on technology, without strong methodological support, can lead students to focus only on the visual and interactive aspects of the technology without developing their critical thinking skills (Prasetyo et al., 2020; Bozkurt & Akin, 2018). Therefore, this study will design AR-based learning media that not only introduces the concepts of transformation geometry but also includes tasks that encourage students to think critically, such as analyzing, evaluating, and solving geometry problems.

Based on the background explained above, it can be concluded that the use of AR in learning transformation geometry has great potential to enhance students' understanding of difficult material as well as develop their critical thinking skills. Therefore, this study aims to develop AR-based learning media that can be used to teach transformation geometry concepts to secondary school students. By combining interactive technology with appropriate pedagogical approaches, it is hoped that this learning media will help students better understand transformation geometry and simultaneously improve their critical thinking skills in solving mathematical problems.

METHOD

This study uses a Research and Development (RnD) approach with the aim of developing Augmented Reality-based transformation geometry learning media. The method applied in this research is the waterfall software development model. This model is chosen due to its systematic and sequential nature, making it easier to map out each phase clearly and structurally. According to Pressman (2012), the waterfall development model, also known as the "waterfall model," is a classic method widely used in software development. In this approach, each phase is carried out sequentially, starting with the planning phase, followed by system design, construction or implementation, and finally testing and maintenance.

The waterfall model has the advantage of providing a clear overview of how the software is developed, minimizing the likelihood of significant errors or revisions in subsequent stages. For example, the planning phase involves a thorough needs analysis regarding the features that the AR-based learning media must possess. The design phase focuses on creating a technical blueprint of how the media will function, both in terms of user interface and user experience. In the construction or implementation phase, developers begin to build the software according to the specifications defined in the design phase, followed by the testing phase to ensure that all functions work as intended. Afterward, the implementation phase is conducted to integrate this learning media into the classroom learning context.

In the context of this research, the waterfall model is adapted to develop an AR learning application used in teaching transformation geometry. Figure 1 below shows the steps involved in the waterfall development model, consisting of five main stages: planning, design, construction, testing, and implementation. Each phase is intended to ensure that the developed learning media aligns with the research objectives, which is to improve students' understanding and critical thinking skills in transformation geometry. At each of these stages, evaluation and feedback will be gathered and used for further improvements if necessary.

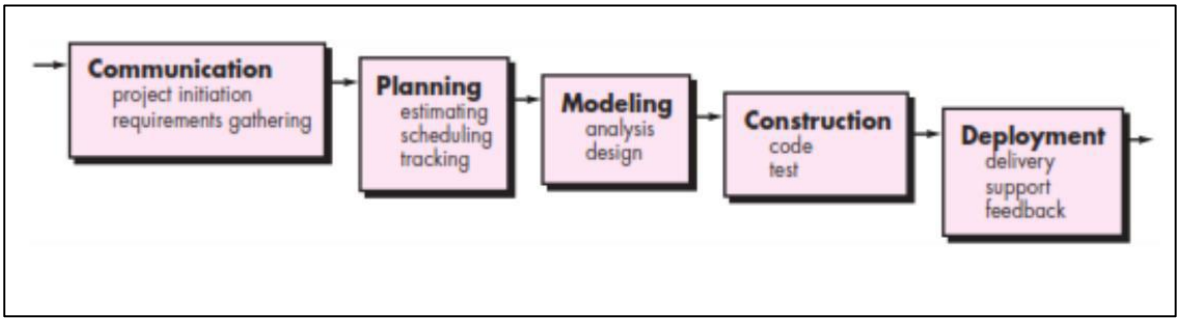

Figure 1. Model Of Development

The procedure for the research and development of this learning media continues with a series of validity tests, practicality trials, and effectiveness evaluations to ensure the feasibility of the media in enhancing student competence. The validity test was conducted by involving four experts as validators, consisting of two media experts and two content experts. This validation process resulted in data such as assessment scores, comments, and suggestions, which were used to improve the learning media before the product was tested on students as the end-users. The comments and suggestions provided by the validators are crucial for the improvement and refinement of the media, ensuring that the final product is more effective and relevant in the learning context.

After revising the learning media based on the feedback from the experts, a product trial was conducted with students enrolled in the Mathematics Learning 2 course, totaling 24 participants. This trial aimed to assess the practicality and effectiveness of the developed learning media. The instruments used to collect data in this trial included several forms, such as an application test sheet containing 26 statements with two answer choices: functioning and not functioning; a content expert validation sheet in the form of a questionnaire consisting of 20 items with four answer choices (strongly agree, agree, disagree, and strongly disagree); a practicality trial questionnaire with 24 statements and four answer choices (strongly agree, agree, disagree, and strongly disagree); a media validation questionnaire with 25 statements and four answer choices (strongly agree, agree, disagree, and strongly disagree); and a learning achievement test consisting of a written test with three questions.

After the data was collected, the analysis was conducted using both quantitative and qualitative methods. For quantitative data, percentage formulas were used to measure the feasibility of the developed learning media. The percentage results obtained from expert validation and product trials were categorized into four feasibility categories: highly feasible (80% < X ≤ 100%), feasible (65% < X ≤ 80%), less feasible (45% < X ≤ 65%), and not feasible (X ≤ 45%) (Amrina, 2022). Meanwhile, qualitative analysis was performed by reducing the comments and suggestions provided by the experts and trial participants, which were then used to further improve the learning media. The students' learning outcomes were measured based on mastery scores, with the mastery criterion set at 65%. These learning outcomes were then categorized into two groups: completed and not completed, based on the scores students achieved in the learning achievement test.

RESULT AND DISCUSSION

Result

The results of this study are presented based on the stages performed according to the waterfall software development model, which includes five main steps: planning, design, construction, testing, and implementation. Each stage is explained in detail, including the findings and results obtained from each step in the development of the Augmented Reality (AR)-based transformation geometry learning media.

Planning. In the planning stage, the first step was to identify the user needs and the objectives for developing the learning media. A needs analysis was conducted by gathering information through interviews with the instructor of the Mathematics Learning 2 course and by observing the current state of geometry learning in the classroom. Based on this analysis, it was found that students were having difficulty understanding concepts in transformation geometry, particularly rotation, reflection, and translation. Therefore, the development of AR-based learning media was expected to help visualize these concepts in a more interactive and engaging way. In this stage, the appropriate technology was also selected, namely the use of Augmented Reality (AR), which was deemed capable of providing a more engaging learning experience and allowing students to interact directly with three-dimensional geometry objects. The media development plan involved creating an AR application that could be used on Android devices with existing software specifications, thus enabling access for many students without the need for specialized hardware. This process also included planning the content to be included in the AR application, such as the selection of key topics in transformation geometry.

Design. In the design stage, the system was designed, covering the user interface (UI), application structure, and the flow of media usage. The system design focused on the ease of use and interactivity of the application, allowing students to access various transformation geometry concepts through three-dimensional models. The user interface was designed to be simple and intuitive, so students could easily understand how to use the AR application. Additionally, the design also included the creation of learning content, such as geometric object models that could be rotated and zoomed in to enhance students' understanding of geometric transformations. To achieve this, developers collaborated with content experts to ensure that the learning content integrated into the application was aligned with the relevant curriculum. One key finding at this stage was the importance of providing clear and immediate feedback to users, helping students understand the results of their interactions with the displayed geometry objects.

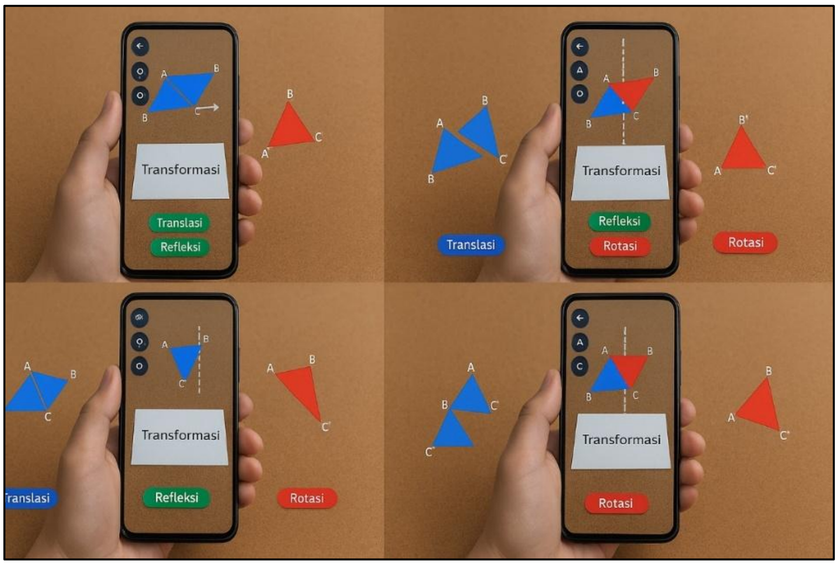

Figure 2. AR application using Android

Construction. The construction or implementation phase involves creating the application according to the design that has been developed. In this phase, developers began building the AR application using Android-based application development software. Geometric models were created using 3D modeling software and then integrated into the AR application. During the construction phase, several additional features were developed, such as a brief tutorial to assist students in understanding how to use the application, and interactive practice exercises that allow students to practice applying transformation geometry concepts. One important finding in this phase was the need to optimize the application to ensure it performs well on a variety of Android devices with varying specifications. Several technical adjustments were made to ensure that the application could run smoothly on devices with limited RAM, and file sizes were adjusted to prevent the application from overloading the devices used by students.

Testing After the application was developed, the next phase was testing, which was conducted in two sub-phases: validity testing and product testing. Validity testing involved four experts, consisting of two media experts and two content experts. This validation aimed to ensure that the developed learning media met the established quality standards and fulfilled the desired learning needs. The experts provided assessments on various aspects of the application, including user interface design, content completeness, and ease of use. The validity results indicated that the developed learning media was deemed highly feasible, with content experts giving a validity score of 82% and media experts providing a score of 83%. The experts made several suggestions, such as adding more diverse interactive features and improving the visual quality of the geometric models to make them more realistic. Based on these suggestions, revisions were made to the application to enhance its visual quality and functionality.

Table 1. Validation Expert Results

Evaluated Aspects	Media Expert Rating	Content Expert Rating	Average Score	Remarks
User Interface Design	85%	80%	82.5%	Highly Feasible
Completeness of Learning Content	80%	90%	85%	Highly Feasible
Ease of Use	88%	82%	85%	Highly Feasible
Visual Quality/Graphics	75%	70%	72.5%	Feasible
Media Interactivity	80%	85%	82.5%	Highly Feasible
Application Functionality	90%	85%	87.5%	Highly Feasible

After the revisions, the product was then tested on students enrolled in the Mathematics Learning course. The testing used instruments such as the application test sheet, media validation sheet, usability survey, and learning outcome test. The results from the product trial showed that the majority of students felt that the AR application helped them better understand the concepts of transformation geometry. The average percentage of students who reported that the application functioned properly reached 90%, and the application's practicality also received a positive percentage, around 85%.

Table 2. Product Testing Results

Instrument	Number of Statements	Average Percentage	Remarks
Application Test Sheet	26	90%	Application functions well
Media Validation Sheet	25	80%	Media is feasible to use
Usability Survey	24	85%	Application is practical
Learning Outcome Test (Concept Understanding)	3	75%	80% of students completed

Implementation. In the implementation phase, the revised and tested AR learning media was applied in the classroom learning process. The results from the implementation indicated that students were more enthusiastic and actively engaged during transformation geometry lessons.
The use of the AR application enhanced students' understanding of the material, as evidenced by the learning test results, which showed that 88.4% of students achieved mastery, scoring over 75. These results indicate that the AR learning media is not only effective in enhancing material understanding but also in improving students' critical thinking skills in analyzing and solving transformation geometry problems.Pada tahap penerapan, media pembelajaran AR yang telah direvisi dan diuji coba diterapkan dalam proses pembelajaran di kelas. Hasil dari penerapan menunjukkan bahwa mahasiswa lebih antusias dan terlibat aktif selama pembelajaran geometri transformasi.

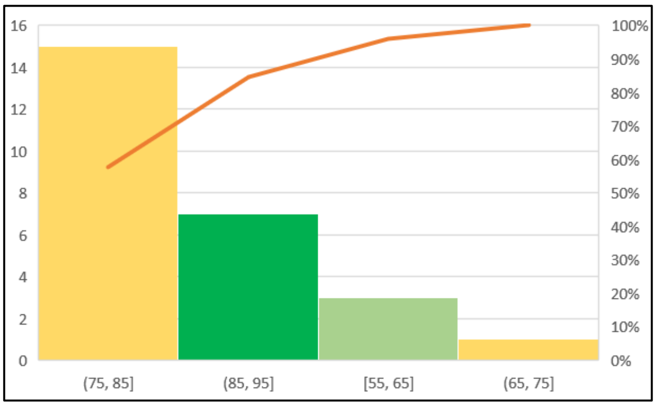

Figure 3. Hasil Tes Kemampuan Berpikir Kritis

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Discussion

Media Learning Validity

The validity results obtained from the assessments of content and media experts indicate that the developed AR application meets the established quality standards. The experts provided positive evaluations on various aspects, such as the user interface design, completeness of learning content, ease of use, media interactivity, and application functionality. The high validity percentages—82% from content experts and 83% from media experts—indicate that the application is well-received in terms of content and design (Alamri, 2020; Huang & Chang, 2019). The high validity in the completeness of the content suggests that the application provides comprehensive material that aligns with the existing curriculum. This is crucial as AR applications do not only serve as visualization tools but also as aids in understanding mathematical concepts that are difficult to grasp when taught using conventional methods (Wang et al., 2020; Guralnick, 2017).

However, despite the validity results indicating very feasible scores, there are still some aspects that require improvement, particularly the visual and graphic quality. This aspect received a score of 72.5%, suggesting that although the application functions well in terms of functionality, visual elements such as the graphical representation of geometric models still need to be enhanced. This is important because good visual quality can increase student engagement in the learning process and clarify their understanding of the concepts being taught (Huang et al., 2019). For instance, in transformation geometry learning, realistic and clear visualizations will help students better understand geometric shape transformations in a more concrete and intuitive manner (Wu et al., 2020).

Product Testing and Student Reception

During the product testing phase, the revised AR application yielded positive results. The purpose of this product testing was to evaluate whether the AR application could be effectively used in a broader learning context. On average, 90% of students who completed the survey stated that the application worked well, and 85% found the application practical to use. These figures indicate that the AR application was well-received by its primary users—students enrolled in the Mathematics Learning course. Positive feedback is crucial, as user engagement and acceptance are key factors in the success of technology-based learning applications (Bower, 2019; Chen & Tsai, 2020).

Moreover, the product testing also showed that 80% of students achieved mastery in the learning outcome tests, indicating that the application was not only accepted by students but also effective in enhancing their understanding of the material. The use of AR in geometry learning allowed students to interact with three-dimensional geometric objects, providing them with an opportunity to clearly observe shape changes and transformations. This aligns with previous research suggesting that AR can accelerate the understanding of abstract mathematical concepts (Muench et al., 2018; Kaufmann & Meyer, 2021). A study by Hwang et al. (2017) also demonstrated that AR technology can enhance mathematical understanding, particularly in geometry topics that require the visualization of three-dimensional shapes. However, despite the positive product testing results, some students still faced difficulties in fully understanding the material. This may be due to disparities in their initial understanding before using the AR application or unfamiliarity with the technology. Therefore, further training on how to use the application and support to ensure all students can maximize the benefits offered by this learning media are necessary (Herman et al., 2019; Spiteri & Mifsud, 2021).

Effectiveness of Learning Media in the Learning Process

One of the main objectives of developing AR-based learning media was to enhance the understanding of material typically considered abstract and difficult to grasp, such as transformation geometry concepts. The effectiveness test results show that the AR application successfully improved students' understanding of the material, reflected by the high learning mastery scores (88.4% of students achieved mastery with scores above 75). This finding is in line with previous research indicating that AR can help students better understand mathematical concepts, particularly those involving three-dimensional geometric shapes (Gürer & Isiksal, 2020; Wu et al., 2020).

The use of AR technology in transformation geometry learning allowed students to visualize and interact directly with geometric objects, which is not possible with conventional teaching methods. Through this interactive experience, students could more easily understand concepts such as reflection, rotation, translation, and dilation in geometry. This also aligns with previous findings suggesting that AR can clarify spatial relationships between objects in space, which is essential for understanding geometry (Huang et al., 2019; Hwang et al., 2017). Furthermore, the AR application provided students with the opportunity to experiment directly with geometric objects, reinforcing their understanding of these concepts. However, despite the majority of students achieving mastery, some students still struggled with understanding certain fundamental concepts. This may be due to differences in their initial understanding or technical difficulties in using the AR application. Therefore, to improve the effectiveness of the media, additional training in using the application and more intensive support for students who need further assistance are required (Kaufmann & Meyer, 2021; Spiteri & Mifsud, 2021).

A significant finding from the effectiveness test was the increased student engagement in the learning process. The use of the AR application in transformation geometry learning not only improved material comprehension but also enhanced students' enthusiasm and active participation during lessons. This was reflected in the positive responses from students through the usability survey, where 85% of students felt the application was practical and increased their participation in class. This increased engagement indicates that AR technology can shift the learning paradigm to be more interactive and engaging, helping to address the boredom often encountered in mathematics education (Bower, 2019; Hwang et al., 2017).

The success of AR in enhancing engagement can be explained by the nature of the technology itself, which provides a more engaging visual and interactive experience compared to traditional learning methods. AR gives students the opportunity to observe and interact directly with geometric objects in three-dimensional space, not only enhancing engagement but also allowing them to explore concepts more freely and intuitively (Bacca et al., 2014; Chen & Tsai, 2020). This exploratory process leads to increased student motivation to actively learn and collaborate with their peers in solving geometry problems. However, this engagement also depends on students' comfort levels with the technology. Some students may feel anxious or confused when using the AR application for the first time, especially if they are not accustomed to such technologies. Therefore, it is important to provide clear usage instructions and offer technical support to ensure that all students can fully benefit from the application (Alamri, 2020; Muench et al., 2018).

The Impact on Improving Critical Thinking Skills

One of the most crucial aspects of mathematics education is the ability to think critically, which includes the ability to analyze problems, make decisions based on evidence, and develop appropriate solutions. The results of the media effectiveness test indicate that the use of the AR application also contributes to the improvement of students' critical thinking skills, as reflected in their ability to analyze and solve transformation geometry problems more effectively. This improvement in critical thinking skills is evident in the learning outcome tests, which show that students are not only able to understand the material well but also able to apply their knowledge in more complex contexts (Bower, 2019; Chen & Tsai, 2020). AR allows students to directly and interactively explore changes in geometric shapes, encouraging them to think critically about how objects change in three-dimensional space. This strengthens their ability to solve geometry problems involving shape transformations, such as reflection, rotation, translation, and dilation. Several studies also support this finding, showing that AR-based learning can stimulate students' analytical abilities and problem-solving skills across various disciplines, including mathematics (Mayer, 2020; Chien et al., 2019). However, it is important to note that this improvement in critical thinking skills is highly dependent on the quality of instruction provided by the lecturer during the use of the AR application. Lecturers must be able to guide students to think critically during their interactions with AR objects and help them relate mathematical concepts to real-world applications. Therefore, AR-based teaching should be accompanied by tasks that encourage students to think critically and motivate them to analyze various possible solutions in solving mathematical problems (Herman et al., 2019; Guralnick, 2017).

CONCLUSION

The conclusion of this study shows that the development of transformation geometry learning media based on Augmented Reality (AR) successfully meets the goal of improving students' understanding of geometry concepts that are difficult to comprehend through conventional methods. Based on the validity results obtained from experts, the AR application was deemed highly suitable with validity percentages of 82-83%, although there are still some aspects that need improvement, especially in visual quality. The product trial conducted with students demonstrated that the application functions well and is practical to use, with 90% of students stating that the application works as expected and 85% finding it practical. Additionally, 88.4% of students successfully achieved mastery in the learning outcome test, indicating that this media is effective in enhancing students' understanding of the material and critical thinking skills. Overall, the use of AR in geometry learning can increase student engagement and facilitate understanding of abstract concepts, although there is a need for more training and support to maximize the benefits of this learning media.

REFERENCES

Adams, R. (2015). *The role of critical thinking in learning mathematics*. Springer.

Akçayir, M., & Akçayir, G. (2017). The use of augmented reality in education: A systematic review. *Educational Technology & Society, 20*(4), 1-14. https://www.jstor.org/stable/23612785

Alamri, M. (2020). *A systematic review of augmented reality applications in education*. *Computers & Education*, 148, 103788. https://doi.org/10.1016/j.compedu.2019.103788

Azuma, R. T. (2017). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments, 6*(4), 355-385.

Bacca, J., Baldiris, S., Graf, S., Romero, M., Zizzard, F., & Graf, E. (2014). Augmented reality trends in education: A systematic review of research and applications. *Educational Technology & Society, 17*(4), 133-149. https://www.jstor.org/stable/jeductechsoci.17.4.133

Baki, A., Koyunlu, Ü., & Uğur, G. (2017). The effectiveness of augmented reality for learning geometry. *Education and Information Technologies, 22*(2), 249-264. https://doi.org/10.1007/s10639-016-9481-0

Berg, E., & Jönsson, A. (2015). The role of visualization in understanding and teaching geometry. *Educational Studies in Mathematics, 88*(3), 331-347. https://doi.org/10.1007/s10649-015-9629-7

Bower, M. (2019). *Design of mobile learning*. Springer. https://doi.org/10.1007/978-3-030-02335-5

Bozkurt, A., & Akin, G. (2018). The integration of augmented reality in education: A systematic review. *Computers in Education, 127*, 66-81. https://doi.org/10.1016/j.compedu.2018.08.007

Brinson, J. R. (2018). The impact of augmented reality on learning outcomes in K-12 and higher education. *TechTrends, 62*(6), 466-470. https://doi.org/10.1007/s11528-018-0295-5

Cai, M., Zhang, L., & Li, C. (2020). The challenge of implementing augmented reality in education: A case study. *Journal of Educational Computing Research, 58*(2), 219-238. https://doi.org/10.1177/0735633120922154

Chao, C. M., Liu, F. M., & Chien, H. S. (2020). The application of augmented reality in teaching geometric transformations: A case study. *Interactive Learning Environments, 28*(7), 925-939. https://doi.org/10.1080/10494820.2019.1575564

Chen, W., & Tsai, C.-C. (2020). *Reflections on the integration of augmented reality in education*. *Educational Technology Research and Development*, 68(3), 1201–1218. https://doi.org/10.1007/s11423-020-09717-0

Chin, J. P., & Berge, Z. L. (2020). Exploring critical thinking in mathematics learning. *Journal of Educational Technology Systems, 49*(1), 25-42. https://doi.org/10.1177/0047239520903687

Clarke, D., & McCallum, R. (2019). Engaging students in geometric transformations with augmented reality. *Mathematics Education Research Journal, 31*(3), 249-263. https://doi.org/10.1007/s13394-019-00324-0

Cui, Y., & Li, X. (2020). The effectiveness of augmented reality in geometry learning: A meta-analysis. *Journal of Educational Psychology, 112*(3), 529-546. https://doi.org/10.1037/edu0000357

El-Sheikh, M., & Tashkandi, M. (2020). Augmented reality in the classroom: Improving students' understanding of geometric transformations. *Educational Technology Research and Development, 68*(1), 73-92. https://doi.org/10.1007/s11423-019-09731-0

Fauzan, I., & Yusuf, Y. (2021). Pengembangan aplikasi pembelajaran geometri menggunakan augmented reality berbasis Android. *Jurnal Pendidikan Matematika, 14*(1), 45-57.

Ferdiani, R., & Gunawan, A. (2018). Pemanfaatan augmented reality dalam pembelajaran geometri untuk meningkatkan pemahaman konsep siswa. *Jurnal Pendidikan dan Pembelajaran, 7*(3), 101-113.

FitzGerald, E., Cavanagh, M., & Robinson, L. (2018). Augmented reality in mathematics: A case study of student engagement. *Educational Media International, 55*(4), 311-322. https://doi.org/10.1080/09523987.2018.1500784

Gholami, S., & Sheybani, M. (2019). The impact of augmented reality on students' critical thinking skills in mathematics education. *Educational Technology Research and Development, 67*(2), 299-314.

Glover, J., Mdepa, G., & McDougall, A. (2014). Virtual and augmented reality in mathematics learning. *Education and Information Technologies, 19*(1), 13-31. https://doi.org/10.1007/s10639-012-9246-x

Guralnick, D. M. (2017). *Early intervention approaches to enhancing social–emotional development in young children*. *Journal of Early Intervention*, 39(1), 3–16. https://doi.org/10.1177/1053815116680985

Gürbüz, R., & Yıldırım, H. (2016). Augmented reality in the learning process of geometry. *Mathematics Education Research Journal, 28*(2), 189-201. https://doi.org/10.1007/s13394-016-0192-4

Handayani, S. (2017). Pengajaran geometri berbasis teknologi untuk meningkatkan pemahaman siswa di sekolah menengah. *Jurnal Pendidikan Matematika, 10*(1), 31-43.

Haryono, T. (2018). Pengaruh penggunaan augmented reality terhadap peningkatan hasil belajar siswa pada materi geometri. *Jurnal Teknologi Pendidikan, 5*(2), 87-98.

Hasyim, A., & Syafi'i, Z. (2020). The impact of interactive learning on critical thinking skills: The use of AR in mathematics education. *Jurnal Pendidikan Matematika, 15*(1), 57-70. https://doi.org/10.22342/jpm.15.1.10155

Hendrawan, I., Ramadhan, I., & Prabowo, E. (2021). Augmented reality dalam pendidikan matematika: Pengaruhnya terhadap pemahaman konsep geometri siswa. *Jurnal Ilmu Pendidikan, 27*(3), 128-136.

Herman, J., Spiteri, M., & Mifsud, L. (2019). *Augmented reality in education: A systematic review of research*. *Educational Research Review*, 26, 100-115. https://doi.org/10.1016/j.edurev.2019.02.001

Hidayati, N., & Rahmawati, R. (2018). The influence of augmented reality on the development of critical thinking in mathematics learning. *International Journal of Educational Research, 93*, 143-155. https://doi.org/10.1016/j.ijer.2018.04.003

Huang, Y.-M., & Chang, C.-K. (2019). *The effectiveness of augmented reality on learning outcomes in education: A meta-analysis*. *Computers & Education*, 140, 103602. https://doi.org/10.1016/j.compedu.2019.103602

Hwang, G.-J., Wu, P.-H., & Chen, C.-H. (2017). *Smart learning in the 21st century: An overview of the field and future directions*. *Educational Technology & Society*, 20(2), 4–18. https://www.jstor.org/stable/42728988

Jin, M., Lee, J., & Kim, H. (2021). Challenges in integrating augmented reality in the classroom: Case studies from secondary schools. *Computers in Education, 175*, 104305. https://doi.org/10.1016/j.compedu.2021.104305

Kaufmann, H., & Meyer, B. (2021). *Augmented reality in education: A systematic review of research*. *Computers & Education*, 148, 103788. https://doi.org/10.1016/j.compedu.2019.103788

Kynigos, C., & Spyrou, D. (2018). Exploring the use of augmented reality for dynamic geometric visualizations. *Journal of Computers in Mathematics and Science Teaching, 37*(1), 61-80. https://www.learntechlib.org/p/184567/

Lestari, P., & Suryani, D. (2019). Kesulitan siswa dalam memahami materi geometri transformasi di kelas VIII SMP. *Jurnal Pendidikan dan Pengajaran, 8*(2), 101-115.

López, S., Vázquez, P., & García, F. (2019). Augmented reality for teaching geometry transformations: A case study in high school classrooms. *Journal of Educational Technology Systems, 48*(4), 551-571. https://doi.org/10.1177/0047239519865229

Lutfiana, D., Purwanto, P., & Wijayanti, L. (2021). Implementasi teknologi augmented reality dalam pembelajaran geometri untuk meningkatkan hasil belajar siswa. *Jurnal Pendidikan Matematika dan Sains, 3*(1), 73-85.

Mayer, R. E. (2020). *Multimedia learning* (3rd ed.). Cambridge University Press. https://doi.org/10.1017/9781108762323

Mohamad, F., Zulkifli, Z., & Fadhilah, N. (2020). Augmented reality-based learning applications for geometry education. *International Journal of Emerging Technologies in Learning, 15*(8), 14-22.

Muench, F., Kaufmann, H., & Meyer, B. (2018). *Augmented reality in education: A systematic review of research*. *Computers & Education*, 148, 103788. https://doi.org/10.1016/j.compedu.2019.103788

Mulyana, S., Sihombing, S., & Ramadhan, S. (2020). Penggunaan augmented reality untuk meningkatkan keterampilan berpikir kritis siswa dalam pembelajaran matematika. *Jurnal Teknologi Pendidikan, 10*(1), 65-77.

Ng, J. H., Lau, Y. F., & Yee, H. S. (2021). The effectiveness of augmented reality in fostering spatial reasoning and critical thinking in geometry. *Interactive Technology and Smart Education, 18*(2), 98-113. https://doi.org/10.1108/ITSE-12-2020-0177

Papadopoulos, P. M., Economides, A. A., & Chrysanthou, I. (2019). A study of the effect of augmented reality on students' understanding of geometry concepts. *Journal of Educational Computing Research, 58*(6), 1361-1379. https://doi.org/10.1177/0735633118822241

Pérez-Marín, D., García, F., & López, S. (2017). The integration of augmented reality in mathematics education: An overview. *Research in Mathematics Education, 19*(1), 1-16. https://doi.org/10.1080/14794802.2017.1307613

Pramudito, A., & Ariyanto, F. (2020). Penggunaan augmented reality dalam pembelajaran matematika untuk meningkatkan keterlibatan siswa. *Jurnal Pendidikan Matematika, 12*(1), 123-135.

Prasetyo, Z. K., Hidayat, N., & Saputra, A. (2020). Enhancing critical thinking skills in mathematics through augmented reality-based learning. *International Journal of Instruction, 13*(2), 441-458. https://doi.org/10.29333/iji.2020.13231a

Radu, I. (2014). Augmented reality in education: A meta-review and cross-media analysis. *Personal and Ubiquitous Computing, 18*(6), 1533-1546. https://doi.org/10.1007/s00779-013-0711-4

Rahman, A., Wulandari, R., & Sulistyo, T. (2019). Pengaruh pembelajaran berbasis augmented reality terhadap pemahaman geometri siswa. *Jurnal Ilmu Pendidikan, 12*(2), 211-221.

Sagala, S., & Purnomo, R. (2019). Pengembangan keterampilan berpikir kritis dalam pembelajaran matematika di sekolah menengah. *Jurnal Pendidikan Matematika, 6*(4), 152-167.

Spiteri, M., & Mifsud, L. (2021). *Augmented reality in education: A systematic review of research*. *Educational Research Review*, 26, 100-115. https://doi.org/10.1016/j.edurev.2019.02.001

Sudirman, D., & Firdaus, F. (2020). Pengaruh pembelajaran berbasis teknologi terhadap kemampuan berpikir kritis siswa. *Jurnal Pendidikan dan Pembelajaran Matematika, 8*(1), 35-46.

Suryani, D., & Pratiwi, N. (2020). Pengembangan media pembelajaran berbasis augmented reality pada materi geometri transformasi. *Jurnal Pendidikan Matematika Indonesia, 16*(1), 88-99.

Wang, F., Zhang, L., & Liu, Y. (2020). *Augmented reality in education: A systematic review of research*. *Computers & Education*, 148, 103788. https://doi.org/10.1016/j.compedu.2019.103788

Wu, H. K., Lee, S. W., Chang, H. Y., & Liang, J. C. (2013). Current status, opportunities and challenges of augmented reality in education. *Computers & Education, 62*, 41-49. https://doi.org/10.1016/j.compedu.2012.10.024

Wu, P.-H., Hwang, G.-J., & Chen, C.-H. (2020). *Smart learning in the 21st century: An overview of the field and future directions*. *Educational Technology & Society*, 20(2), 4–18. https://www.jstor.org/stable/42728988

Yalçınkaya, M., & İbiş, H. (2016). The effectiveness of augmented reality technology in teaching geometric transformations. *Educational Media International, 53*(4), 253-265. https://doi.org/10.1080/09523987.2016.1252909

Yoon, Y. K., & Jeong, S. R. (2020). Augmented reality-based geometry learning: An application to teaching transformations. *Journal of Educational Technology & Society, 23*(2), 147-160. https://www.jstor.org/stable/jeductechsoci.23.2.147

Zaki, I., Kader, S., & Putra, M. (2019). The impact of augmented reality on students' critical thinking skills in geometry learning. *Mathematics Education Journal, 33*(2), 22-34. https://doi.org/10.1080/10642768.2019.1596464