2025, 6(1), 71–83

Journal of Didactic Mathematics
https://doi.org/10.34007/jdm.v6i1.2588

# Enhancing critical thinking skills through GeoGebra-based learning media in geometry transformation lessons for grade 11 students

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**Abstract.**
This study aims to develop and test the effectiveness of GeoGebra-based mathematics learning media on the critical thinking skills of 11th-grade high school students in the topic of geometric transformations. The research employed the ADDIE development model, consisting of five stages: analysis, design, development, implementation, and evaluation. During the analysis stage, interviews and pre-tests were conducted to identify students' needs and assess their initial abilities. The design stage involved creating GeoGebra-based learning media, developing assessment instruments, and designing lesson plans (RPP) using the PMRI model. In the development stage, the learning media were validated by media and content experts and tested on students of class XI MIPA 3 at SMA Negeri 1 Bangorejo. The implementation stage consisted of two sessions for teaching and testing. The evaluation stage included analyzing pre-test and post-test results using N-gain tests, normality tests, homogeneity tests, and paired sample t-tests. The results showed that the GeoGebra-based learning media achieved an excellent level of validity, with media validity at 95% and content validity at 85%. Furthermore, the media were rated as highly practical by students, with an average questionnaire score of 85%. The N-gain test indicated a "moderately effective" category with an average score of 56%. The paired sample t-test yielded a significance value of 0.000, demonstrating a significant improvement in students' critical thinking skills after using the media. Thus, it can be concluded that GeoGebra-based mathematics learning media are valid, practical, effective, and positively impact students' critical thinking skills in geometric transformations.

**Keywords:**
Learning media; GeoGebra; Critical thinking skills; Geometric transformations

**How to cite:**
Adiguna, K. A., Sunardi, S., & Prastiti, T. D. (2025). Enhancing critical thinking skills through GeoGebra-based learning media in geometry transformation lessons for grade 11 students. *Journal of Didactic Mathematics*, *6*(1), 71–83. https://doi.org/10.34007/jdm.v6i1.2588

## INTRODUCTION

Education assumes a pivotal role in shaping superior, independent, and adaptable human resources, equipping them to effectively address the increasingly intricate global challenges. In the current era of disruption, a nation's ability to compete in the international arena is significantly influenced by the quality of its education system. Education's primary objective extends beyond mere life education; it also serves as the cornerstone in developing the spiritual, intellectual, emotional, and skill potential of students. As aptly articulated by Abd Rahman et al. (2022), education is a deliberate and systematic endeavor to establish a learning environment that facilitates optimal development in all dimensions of human flourishing. Within this context, education is comprehensively regarded as a holistic process that transcends the sole focus on cognitive aspects, encompassing affective and psychomotor dimensions as well. Furthermore, education plays a

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Received: 15 February 2025; Revised: 09 April 2025; Accepted: 17 April 2025

crucial role in enhancing the quality of life and competitiveness of a nation. Nugraheni and Sudarwati (2021) underscore the significance of quality education as the pivotal foundation for driving economic growth, fostering social stability, and propelling the advancement of civilization. This aligns with UNESCO's (2021) perspective, which posits that 21st-century education must equip individuals with essential literacy, 21st-century skills, and socio-emotional competencies, thereby equipping them to effectively confront global challenges. Consequently, the education system must continuously evolve in response to societal dynamics and technological advancements to maintain its relevance and meet the evolving demands of the contemporary era.

The advancement of science and technology has profoundly transformed the educational landscape. Notably, the learning methodology has undergone a significant shift. While traditional learning emphasized a teacher-centered approach, the current paradigm has transitioned towards a more participatory and student-centric model. Technological learning media plays a pivotal role in enhancing the efficacy of the teaching and learning process. By bridging the gap between abstract concepts and students' concrete comprehension, these media facilitate increased learning engagement and motivation (Kuş, 2025; Wulandari et al., 2023; Murad et al., 2019; Chauhan, 2017).

Within the domain of mathematical education, the incorporation of technological tools has been demonstrated to enhance students' conceptual comprehension and critical thinking abilities. Software applications such as GeoGebra, Maple, and others have gained prominence in interactive learning environments, facilitating students' intuitive and visual grasp of intricate concepts (Buteau et al., 2014). Notably, GeoGebra has garnered recognition as an exceptionally effective learning instrument in fostering simultaneous comprehension of geometry and algebra (Seftiana et al., 2024; Zetriuslita et al., 2020).

Mathematics, as a fundamental scientific discipline, significantly contributes to the development of logical and critical thinking patterns. Critical thinking skills are of paramount importance in education, as they facilitate problem-solving and decision-making processes grounded in analysis. Fisher (in Fristadi & Bharata, 2015) defines critical thinking as the capacity to discern and analyze issues, synthesize pertinent information, assess alternative solutions, and draw conclusions supported by empirical evidence. Enhancing critical thinking skills has emerged as a primary focus in global mathematics education (Facione, 2015; Yanuari & Turmudi, 2023).

Regrettably, critical thinking skills among Indonesian students remain relatively underdeveloped. A study conducted by Ester and Listiani (2024) indicated that the average mathematical critical thinking score among students was only 51%. Furthermore, the 2018 PISA report revealed that Indonesian students' ability to reason and apply mathematical concepts in practical scenarios is still significantly inferior to the average of OECD countries (OECD, 2019). A primary contributing factor to this disparity is the limited utilization of innovative learning strategies that can foster higher-order thinking, such as the incorporation of technology and contextual approaches.

One effective approach to addressing this challenge is Indonesian Realistic Mathematics Education (PMRI), an adaptation of Realistic Mathematics Education (RME). This approach emphasizes the significance of real-world contexts in mathematical learning and encourages students to construct their own mathematical concepts based on their experiences (Gravemeijer & Doorman, 1999). RME has been demonstrated to be effective in enhancing students' conceptual comprehension and critical thinking abilities (van den Heuvel-Panhuizen, 2001).

In the context of PMRI, students are encouraged to engage in practical problem-solving activities. This approach fosters critical thinking skills by encouraging students to analyze complex issues, generate innovative solutions, and communicate their findings effectively. The principles of active and problem-based learning, as outlined in international literature, have been demonstrated to be an effective method for enhancing critical thinking abilities (Hmelo-Silver, 2004; Loyens et al., 2012).

Geometric transformation is a mathematical subject that lends itself well to the PMRI approach and interactive media such as GeoGebra. This material demands a simultaneous understanding of spatial and symbolic concepts. However, many students encounter difficulties in

comprehending transformations such as reflection, rotation, translation, and dilation, both visually and algebraically. Faizah et al. (2023) identified several contributing factors, including a superficial understanding and a lack of visual-conceptual practice.

GeoGebra offers an educational platform that enables students to engage in dynamic exploration of geometric transformations. Utilizing real-time and manipulative visualizations, students can observe transformations that impact the position, shape, and size of geometric objects. This dynamic approach facilitates a deeper comprehension of the algebraic representations associated with these transformations. Research conducted by Zetriuslita et al. (2020) and Saha et al. (2010) indicate that GeoGebra substantially enhances students' critical thinking abilities, conceptual understanding, and engagement in geometry learning materials.

The incorporation of GeoGebra into the PMRI framework facilitates learning that is not only contextual and pertinent, but also interactive and exploratory. Students not only acquire information, but also assume an active role in constructing knowledge through technology-driven learning experiences and authentic situations. This aligns with the constructivist learning framework, which supports the development of 21st-century competencies (Jonassen, 1999; Schunk, 2012).

In addition, research conducted by Wiyanti and Hadi (2023) corroborates that the utilization of GeoGebra in project-based learning and realistic contexts significantly fosters students' reflective and critical thinking abilities. GeoGebra also facilitates personalization of learning, allowing students to explore concepts at their own pace and learning style.

Furthermore, critical thinking skills are among the primary indicators of 21st-century competencies, as underscored by the Partnership for 21st Century Learning (P21). The Indonesian national curriculum, through the Merdeka Curriculum, also emphasizes the significance of developing competencies such as critical thinking, creativity, and logical reasoning through meaningful learning experiences. Consequently, a learning model that integrates technology (GeoGebra), a contextual approach (PMRI), and reflective activities can serve as a strategic solution to address the challenge of low critical thinking skills among students in Indonesia.

Based on this background, this study endeavors to explore the integration of GeoGebra within the PMRI approach to enhance students' critical thinking skills in geometric transformation material. The study is anticipated to provide theoretical contributions in the development of innovative learning models, as well as practical contributions for mathematics educators in designing adaptive, engaging, and high-level thinking skills-oriented learning experiences.

## METHOD

This study is a Research and Development (R&D) type of research, aimed at developing a new product or improving an existing one (Borg & Gall, 1983). The research was conducted in Grade XI of a senior high school, involving 35 students as the research sample. The product developed was a learning media based on GeoGebra software. The development model used was ADDIE (Analysis, Design, Development, Implementation, Evaluation), selected for its ease of understanding, systematic structure, and focus on producing instructional products grounded in relevant theory and student needs.

The ADDIE model was employed to develop interactive learning media using GeoGebra, with the objective of enhancing students' critical thinking skills on the topic of geometric transformations. The development process was carried out in a structured and systematic manner, starting from needs analysis, media design, product development, classroom implementation, and culminating in an evaluation of the media's effectiveness. This process took into account the characteristics of students and the challenges encountered during classroom learning, particularly in the visually abstract topic of geometric transformations. The stages of the development process using the ADDIE model are illustrated in Figure 1.

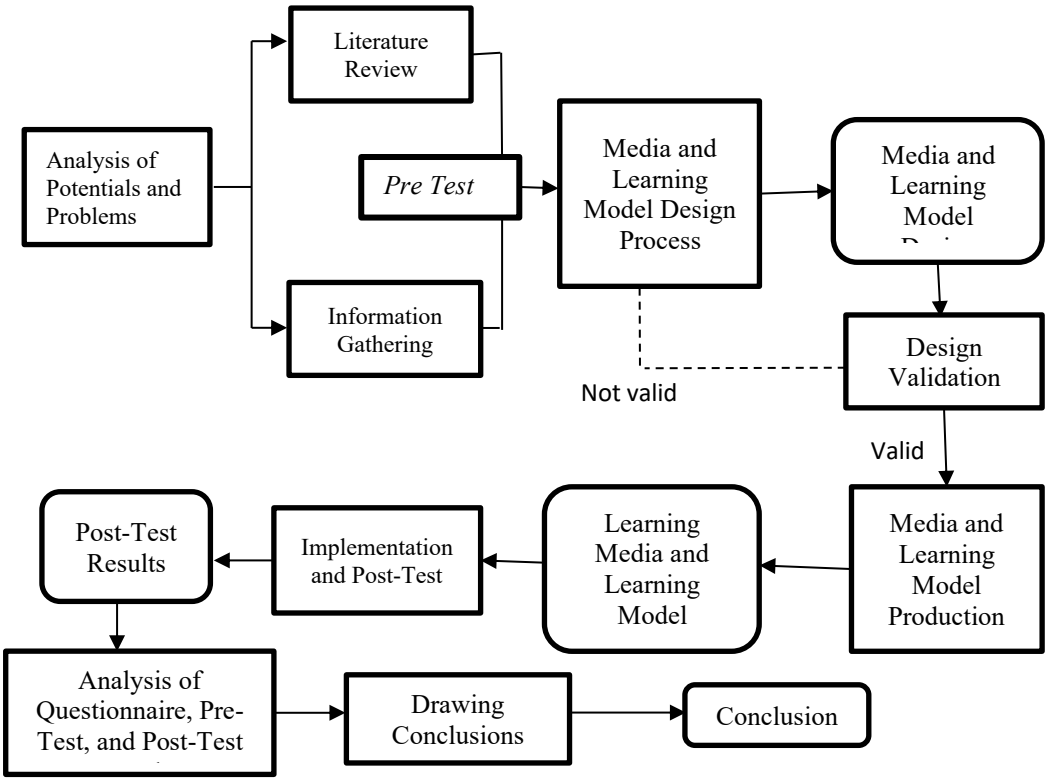


**Figure 1.** Flowchart of the development process of GeoGebra-based mathematics learning media

*Analysis*

The analysis stage aimed to identify instructional needs and challenges faced by teachers and students in understanding geometric transformation concepts. The analysis was conducted through literature review of the curriculum, textbooks, and relevant research journals. In addition, interviews with mathematics teachers were carried out to explore classroom learning difficulties and the potential use of technology-based media. Respondents were selected based on their experience teaching Grade XI and having at least five years of experience teaching mathematics at the senior high school level.

*Design*

The design stage aimed to create a GeoGebra-based learning media aligned with the results of the analysis. During this stage, the development flow of the learning media was designed, starting from defining learning objectives, structuring the material to be presented, and organizing learning activities that support the development of students' critical thinking skills. The media interface was designed to be interactive and appealing, and adapted to the characteristics of high school students. In addition, research instruments were developed to measure media quality and its impact on students. These instruments included validation sheets for content and media experts, practicality questionnaires, and a critical thinking test designed based on critical thinking indicators.

*Development*

In this stage, the initial version of the GeoGebra-based learning media was created using GeoGebra software. The completed product was then validated by four validators—two media experts and two content experts. The validators assessed the product based on content feasibility, visual appearance, interactivity, and alignment with learning objectives. The assessment used a 4-point Likert scale. The validation outcomes were scrutinized to ascertain the product's validity level, employing the criteria outlined in Table 1.

Based on this classification, if the average rating of the media is within the 3.26–4.00 range, it is considered very valid and ready for use. Media that do not meet this category will be revised according to the validators' suggestions before implementation.

**Table 1.** Product validity criteria

| Score range | Validity category |
|---|---|
| 3.26 – 4.00 | Very Valid |
| 2.51 – 3.25 | Fairly Valid |
| 1.76 – 2.50 | Less Valid |
| 1.00 – 1.75 | Not Valid |

*Implementation*

The validated and revised media was implemented in a Grade XI class over two sessions, each lasting 2 × 45 minutes. The learning scenario was designed using the PMRI (Indonesian Realistic Mathematics Education) approach, where students were guided to explore geometric transformation concepts independently or in groups using the GeoGebra media. After the learning activities, students filled out a practicality questionnaire to evaluate ease of use, visual appeal, and the usefulness of the media in supporting their learning. The data collected from the practicality questionnaire was analyzed in accordance with the criteria outlined in Table 2.

**Table 2.** Practicality criteria of learning media

| Score range | Practicality category |
|---|---|
| 3.26 – 4.00 | Very practical |
| 2.51 – 3.25 | Fairly practical |
| 1.76 – 2.50 | Less practical |
| 1.00 – 1.75 | Not practical |

If the average score falls into the "very practical" category, the media is considered suitable for classroom use with minimal revisions. The practicality results also serve as an initial indicator of user acceptance.

*Evaluation*

Evaluation was conducted to measure the effectiveness of the GeoGebra-based learning media in enhancing students' critical thinking skills. The evaluation instruments consisted of pre-test and post-test questions developed based on four critical thinking indicators: interpretation, analysis, evaluation, and inference.

In several stages, the analysis of the pre-test and post-test results was conducted. Initially, the N-Gain score was calculated to assess the enhancement of students' critical thinking skills following participation in the learning intervention employing the media. This N-Gain score provides a comprehensive evaluation of the learning intervention's effectiveness, categorized as follows: a score of $\geq 0.7$ is considered high, a score between 0.3 and 0.7 is categorized as medium, and a score $< 0.3$ is categorized as low.

Subsequently, a normality test was performed to determine whether the pre-test and post-test data adhere to a normal distribution. This test was conducted using the Kolmogorov-Smirnov method through the SPSS application, with the criterion for normal distribution being a significance value (sig.) exceeding 0.05. Subsequently, a homogeneity test was conducted to ascertain whether the variance between the two groups is homogeneous. This test utilized the Levene test through SPSS, and the data was deemed homogeneous if the significance value exceeded 0.05. Finally, a paired sample t-test was employed to evaluate the presence of a significant difference between students' pre-test and post-test scores. This test was conducted through SPSS, with a significance value (2-tailed) less than 0.05 indicating a substantial difference between the two scores.

Based on the results of these analyses, it can be concluded whether the developed GeoGebra-based learning media is effective in enhancing students' critical thinking skills. If all tests yield positive results, the media is considered successful in achieving the development objectives. By following the ADDIE model systematically and utilizing appropriate instruments and analytical techniques, the learning media developed is expected to be not only valid and

practical, but also effective in improving students' critical thinking skills in geometric transformations.

## RESULTS AND DISCUSSION

This study aims to develop GeoGebra-based learning media for geometric transformation material and evaluate its effectiveness in enhancing students' critical thinking skills. The research subjects consisted of 35 students from class XI MIPA 3 at SMA Negeri 1 Bangorejo. The research process followed the stages of the ADDIE model, which includes needs analysis, media design, development, implementation, and evaluation.

During the validation stage, the GeoGebra-based learning media was assessed by two subject matter experts and two media experts. The validation results, presented in Table 3 and Table 4, cover aspects such as content relevance, clarity of usage instructions, completeness of components, readability of symbols, and media design. The learning media was deemed valid without requiring revisions, achieving an average validation percentage of 90%.

**Table 3.** Media validation results by media experts

| No | Validation questions | Score | |
|---|---|---|---|
| | | Validator 1 | Validator 2 |
| 1 | Is the presentation of the material in the GeoGebra media relevant for use in classroom learning? | 4 | 4 |
| 2 | Are the instructions for using GeoGebra media clear for geometric transformation material? | 3 | 2 |
| 3 | Are the components of GeoGebra media (Cartesian coordinates, lines, points, and transformation toolbar) complete for use in geometric transformation material? | 4 | 3 |
| 4 | Does the presentation of the material in the GeoGebra media support the student learning process? | 4 | 4 |
| 5 | Are the images, visuals, and mathematical symbols in the GeoGebra media clearly readable for use in geometric transformation material? | 4 | 4 |
| | Total | 19 | 17 |

Based on the validation results obtained by two media experts, the total scores were 19 and 17 out of a maximum of 20 points, respectively. The validation percentage by Validator 1 reached 95%, while Validator 2 provided a score of 85%. Both percentages are categorized as "valid without revision." The validated aspects encompass the relevance of the material presentation, the clarity of the instructions for use, the completeness of the media components (including Cartesian coordinates, points, lines, and transformation toolbars), the readability of mathematical symbols, and the visual design of the media. However, one indicator received a relatively low score: the clarity of the instructions for using the media, which scored 3 (Validator 1) and 2 (Validator 2). This indicates the need for improvement in this aspect. As a follow-up, improvements were implemented by adding more systematic instructions for use and supporting images to clarify the steps for utilizing GeoGebra.

Two material experts conducted validation, resulting in identical scores of 19 for each validator, representing 95% and 85% validity and classification as "valid without revision." Validation encompasses the material's alignment with fundamental competencies, clarity of instructions, completeness of visual components in the media, support for the student learning process, and readability of the visual display. Notably, there was a slight discrepancy in scores regarding instructions for use and visualization, which are crucial inputs for enhancing the media. Consequently, improvements were implemented by clarifying the display and optimizing visual elements to enhance student comprehension.

The implementation of the learning media was carried out over two sessions. The results of the students' pre-test and post-test on geometric transformation material are shown in Table 5 and

Table 6. The average pre-test score of the students was 81.20, while the average post-test score increased to 90.17.

**Table 4.** Media validation results by learning material experts

| No | Validation questions | Score | |
|---|---|---|---|
| | | Validator 1 | Validator 2 |
| 1. | Is the learning material in the GeoGebra media relevant to the competencies that students must master? | 4 | 4 |
| 2. | Are the instructions for using GeoGebra media clear for learning geometric transformation material | 4 | 3 |
| 3. | Are the components of GeoGebra media (Cartesian coordinates, lines, points, and transformation toolbar) complete for learning geometric transformation material | 4 | 4 |
| 4. | Does the content of the learning material in GeoGebra media support the student learning process? | 4 | 4 |
| 5. | Are the use of images, displays, and mathematical symbols in GeoGebra media clearly readable for learning geometric transformation material? | 3 | 4 |
| | Total | 19 | 19 |

Based on the results of the pre-test administered to 35 students of Class XI MIPA 3 prior to the implementation of GeoGebra-based learning media, an initial assessment of students' critical thinking abilities in geometric transformation material was conducted. The pre-test scores exhibited a range spanning from the lowest value of 68 to the highest value of 95, encompassing a score range of 27. The average value (mean) obtained was 81.20, while the median value was 82.00, suggesting a relatively symmetrical distribution of data. The mode value of 86 indicates that this score represents the most frequent occurrence among students.

**Table 5.** Pre-test results of geogebra learning media

| Descriptive Statistics | Value |
|---|---|
| Minimum Score | 68 |
| Maximum Score | 95 |
| Range | 27 |
| Mean (Average) | 81.20 |
| Median | 82.00 |
| Mode | 86 |
| Standard Deviation | 7.56 |

Furthermore, the standard deviation calculation of 7.56 indicates a moderate distribution of scores. This implies that there exists a degree of variation in students' critical thinking abilities prior to the treatment, albeit within a reasonable range. In general, the pre-test data suggests that a substantial majority of students possess a relatively sound initial comprehension of the fundamental concepts of geometric transformation. However, it is noteworthy that there are still students exhibiting lower abilities, necessitating the implementation of a learning strategy that can effectively address these disparities and foster the equitable development of critical thinking skills among all students.

Consequently, the utilization of GeoGebra-based learning media is anticipated to provide a more contextual, visual, and interactive learning experience, thereby facilitating students' deeper comprehension of the material and the enhancement of their critical thinking abilities. The outcomes of students' post-test are presented in Table 6.

The post-test administered to 35 students after the implementation of GeoGebra-based learning media revealed a substantial enhancement in students' performance on the subject of geometric transformations. The post-test scores ranged from a minimum of 80 to a maximum of 100, encompassing a range of 20 points. The mean score was 90.17, indicating that, on average,

students demonstrated a high level of comprehension after engaging with the instructional media. This observation is further corroborated by the median score of 94.00, suggesting that at least half of the students achieved scores equal to or exceeding this value.

**Table 6.** Post-test results of geogebra learning media

| Descriptive Statistic | Value |
|---|---|
| Minimum Score | 80 |
| Maximum Score | 100 |
| Range | 20 |
| Mean (Average) | 90.17 |
| Median | 94.00 |
| Mode | 98 |
| Standard Deviation | 6.06 |

Additionally, the mode score of 98 indicates that this score was the most frequently obtained by students, reflecting a pronounced clustering of scores in the upper range. The standard deviation of 6.06 suggests a relatively low degree of variability in the data, implying that most students achieved scores close to the average. This consistency in high performance suggests that the utilization of GeoGebra-based media not only enhanced students' comprehension of geometric transformation concepts but also fostered the development of critical thinking skills throughout the class.

Overall, the post-test outcomes demonstrate the efficacy of GeoGebra learning media in facilitating students' academic achievement and understanding of mathematical concepts in a more interactive and meaningful manner. Additionally, the questionnaire data analysis, presented in Table 7, shows a practicality level of 85%. The media was rated highly practical based on aspects such as ease of use, attractiveness, and material presentation.

**Table 7.** Assessment data of student questionnaire responses

| Aspect | Total Score of All Respondents | Average Percentage | Practicality Criteria |
|---|---|---|---|
| Ease of Use | 81 | 81% | Highly Practical |
| Short Time Required | 85 | 85% | Highly Practical |
| Product Appeal | 89 | 89% | Highly Practical |
| Easy to Interpret | 79 | 79% | Practical |
| Material Presentation in Media | 89 | 89% | Highly Practical |
| Overall Average | | 85% | Highly Practical |

Additionally, student interviews were conducted to assess their responses to the GeoGebra-based learning media. A concise summary of the student interview results is presented in Table 8, which underscores that student found this media to be an effective tool for enhancing their comprehension of geometric transformation concepts and fostering a more engaging learning experience.

The student interviews conducted regarding the utilization of GeoGebra-based learning media yielded predominantly positive feedback. A majority of students expressed enthusiasm and engagement during mathematics lessons that incorporated the GeoGebra application, indicating that the media enhanced the learning process by fostering interactivity and enjoyment. Furthermore, students reported a sense of comfort throughout the learning sessions, without encountering substantial difficulties in comprehending the material. This suggests that the visual and dynamic nature of GeoGebra effectively elucidated intricate concepts pertaining to geometric transformations.

In response to inquiries about their learning requirements, students underscored the significance of innovative instructional strategies. They acknowledged that employing educational tools such as GeoGebra can augment their understanding of abstract mathematical concepts,

particularly those associated with transformations. Notably, they regarded the utilization of media not only as beneficial but also as indispensable in facilitating comprehension. Additionally, students responded favorably to the visual design and layout of the GeoGebra media, finding it aesthetically pleasing and engaging.

**Table 8.** Student interview results after learning using GeoGebra media

| No | Question Topic | Summary of Answers |
|---|---|---|
| 1. | Student responses when participating in mathematics learning in class using GeoGebra media. | In general, students' responses were positive when participating in learning using GeoGebra media. |
| 2. | Things that make students uncomfortable when learning in class using GeoGebra media. | In general, students feel comfortable when learning in class using GeoGebra media. |
| 3. | Difficulties faced by students when learning in class using GeoGebra media. | In general, students did not experience learning difficulties in the transformation material because the content was clarified by GeoGebra media. |
| 4. | Students' need for innovative learning (such as the use of media or teaching aids). | In general, students need innovative learning, such as using GeoGebra learning media for transformation material. |
| 5. | The need for GeoGebra learning media to understand concepts in transformation material. | In general, students need a media to understand the concepts of transformation material. |
| 6. | Students' interest in the appearance of GeoGebra learning media on transformation material. | In general, students are highly interested in the appearance of the media. |
| 7. | Students' messages and impressions on the use of GeoGebra-based learning media. | Some students suggested that teachers should use media such as the GeoGebra application more frequently to make learning more innovative and less monotonous.<br>Additionally, students strongly support teachers incorporating media into the learning process. |

Students also provided suggestions and reflections on the continued use of such media in the classroom setting. Several students recommended that educators integrate GeoGebra or analogous digital tools more frequently to render mathematics lessons more dynamic and less repetitive. Overall, the responses collectively demonstrated strong support for the integration of technology in mathematics education and underscored the positive impact of GeoGebra on both the learning experience and conceptual comprehension.

This research aligns with and extends the findings of previous studies, such as those conducted by Ulfah et al. (2023) and Amalia et al. (2020), which demonstrated that technology-based learning media can effectively enhance students' thinking skills. In particular, this study confirms the pedagogical value of GeoGebra as an interactive and dynamic tool for visualizing complex mathematical concepts, such as geometric transformations. The visual and manipulative features of GeoGebra allow students to actively explore and discover relationships among geometric figures, fostering deeper conceptual understanding and higher-order thinking skills (Hidayat et al., 2024; Putra & Siswono, 2021).

The primary advantage of the GeoGebra-based learning media developed in this study lies in its ability to integrate visual representation with interactive elements that directly support the development of critical thinking. This is consistent with the findings of recent international research, which highlights that digital learning environments—especially those incorporating dynamic geometry software—can significantly contribute to students' engagement, reasoning abilities, and reflective thinking (Gurmu et al., 2024; Birgin & Uzun Yazıcı, 2021). By providing immediate feedback, facilitating experimentation, and promoting active inquiry, GeoGebra not

only enhances mathematical comprehension but also aligns with constructivist and realistic learning principles.

The data analysis in this study was designed to measure three key aspects of the media's implementation: effectiveness, practicality, and impact on students' critical thinking skills in the context of geometric transformations. To achieve this, the research employed a multi-stage statistical approach, including the N-gain test, normality test, homogeneity test, paired sample t-test, and practicality questionnaire. The N-gain test resulted in an average score of 0.5633, categorized as moderate, suggesting that the learning media was sufficiently effective in improving students' abilities. This moderate level of gain is consistent with studies showing that technology integration in mathematics classrooms often results in significant, though sometimes gradual, improvements in analytical and reasoning skills (Permatasari et al., 2020).

The normality test using the Kolmogorov–Smirnov method and supported by Q–Q plot analysis confirmed that the data were normally distributed, allowing for parametric analysis. The Levene's test for homogeneity yielded a significance value of 0.869 (> 0.05), indicating that the data variance between pre-test and post-test scores was statistically homogeneous. The paired sample t-test produced a p-value of 0.000 (< 0.05), demonstrating a statistically significant difference between pre-test and post-test scores. This confirms that the implementation of the GeoGebra-based media had a measurable and positive effect on student learning outcomes.

Quantitatively, the average score increased from 81.20 on the pre-test to 90.17 on the post-test, further supporting the effectiveness of the media in enhancing students' performance. These results align with the findings of studies such as those by Alrashidi and Almutairi (2023), which reported similar gains in student achievement and reasoning ability following the use of visual-digital mathematics tools.

In addition to effectiveness, the study assessed the practicality of the media based on student responses to a structured questionnaire. The results indicated an average practicality score of 85%, which falls under the "very practical" category. This finding reflects students' positive perceptions of the media in terms of ease of use, instructional clarity, visual appeal, and alignment with their learning needs. The results resonate with research by Sulistyaningsih et al. (2022), who found that students value media that is intuitive and visually engaging, especially in topics involving abstract spatial reasoning.

In conclusion, the combination of effectiveness data (as shown by learning gains and statistical tests) and practicality data (as indicated by positive student feedback) supports the conclusion that the GeoGebra-based instructional media developed in this study is pedagogically sound, didactically practical, and educationally impactful. Its use in mathematics classrooms, particularly for teaching geometric transformations, is therefore recommended as a strategy to foster critical thinking and deepen conceptual understanding in line with the goals of 21st-century education.

## CONCLUSIONS

The findings of this study demonstrate that the GeoGebra-based instructional media developed for the topic of geometric transformations satisfies the essential criteria of validity, practicality, and moderate effectiveness. The validation results from both media and content experts confirmed that the instructional media is suitable for classroom implementation without requiring revisions. Furthermore, the practicality evaluation, based on student responses, indicated a high level of usability, clarity, and engagement, reflecting students' positive perceptions toward the media. The effectiveness of the media, as measured by learning outcomes, yielded an average N-gain score within the moderate category, suggesting that the media has a meaningful impact on enhancing students' critical thinking skills.

These results underscore the potential of integrating dynamic mathematics software like GeoGebra into classroom instruction to support the development of higher-order thinking. The visual, interactive, and exploratory features of GeoGebra provide students with a more intuitive understanding of abstract mathematical concepts, particularly in topics involving spatial reasoning

such as geometric transformations. The favorable response from students and the statistically significant improvement in their performance further reinforce the pedagogical value of this approach.

In light of these findings, it is recommended that mathematics educators adopt GeoGebra-based instructional media as a complementary tool in teaching geometric transformations. Moreover, the success of this implementation opens opportunities for expanding the use of similar technology-assisted learning media across other mathematical domains, such as functions, algebra, and statistics. Future research and development efforts may focus on adapting and refining GeoGebra-based media to align with various curriculum levels and learner characteristics. In doing so, mathematics instruction can be made more engaging, interactive, and conducive to fostering students' critical and creative thinking skills in alignment with 21st-century educational goals.

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