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Digitization of virtual reality-based ethnomathematics learning to improve students ' mathematical critical thinking in geometry courses

[1]Fikri Apriyono
[1]State Islamic University of Kiai Hajj Achmad Siddiq, Jember, Indonesia

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A B S T R A C T
This study explored the development and effects of a Virtual Reality-based ethnomathematics learning medium aimed at enhancing students' mathematical critical thinking skills in analytic geometry. The study addressed the challenges students encounter in visualizing three-dimensional concepts. A Virtual Reality based learning medium was developed using an R&D framework combined with a quasi-experimental pretest posttest control group design. The learning media were validated by nine experts in content, media, and instructional design, and underwent usability testing with 21 student participants. Quantitative data were gathered from pretest and posttest assessments and analyzed to determine the magnitude of learning gains. The experimental group achieved an average N-Gain score of 0.68, classified as moderate improvement, while the control group attained an N-Gain of 0.61. Qualitative data from classroom observations and open-ended questionnaires provided additional insight into user experience. The results showed that the VR-based tool significantly enhanced students' mathematical critical thinking and was positively rated for usability, navigation, and engagement. Students also appreciated the integration of cultural elements, which enriched their conceptual understanding. These findings highlight the potential of immersive and culturally contextualized media for enhancing students' mathematical critical thinking. The study recommends wider implementation of the developed VR tool and suggests further research focusing on scalability and long-term learning impacts.

*Corresponding author.
E-mail: fikrimath@uinkhas.ac.id

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1. INTRODUCTION

The integration of advanced technologies in education has significantly transformed the delivery and reception of knowledge across disciplines, including mathematics (Attard & Holmes, 2020; Bray & Tangney, 2017; McLeod, 2018). Mathematics is widely acknowledged as a fundamental domain that underpins technological advancement, economic development, and informed citizenship (Heiliö, 2016; Wakayama, 2013). Despite its importance, many students find mathematics, particularly geometry, difficult and abstract (Iwano et al., 2021; Jiménez-Vilcherrez et al., 2023). Geometry often requires strong spatial reasoning and visualization skills, which are challenging for learners to develop through conventional instructional methods (Contreras et al., 2018; Mjenda et al., 2023; Mondido et al., 2024). Consequently, educators are increasingly exploring pedagogical innovations that can enhance students' conceptual understanding and engagement.

One promising pedagogical shift is the incorporation of immersive technologies, such as Virtual Reality (VR) and Augmented Reality (AR), into the teaching of geometry. These tools provide interactive, three-dimensional environments that support spatial visualization and experiential learning (Elamrani & Moughit, 2024; Korenova et al., 2024; Mondido et al., 2024). In addition, integrating ethnomathematics into instructional design ensures that students learn geometry through cultural contexts that are familiar to them, enabling more meaningful knowledge construction. When VR or AR features are utilized to present these cultural representations in three-dimensional space, students can explore mathematical ideas in a way that is simultaneously immersive and culturally grounded, leading to stronger engagement and deeper conceptual understanding. Studies have consistently demonstrated that the application of VR and AR in mathematics education can enhance student motivation and learning outcomes (Kononov et al., 2025; Vashisht, 2024). Parallel to this technological innovation is the ethnomathematics approach, which emphasizes the cultural relevance of mathematical concepts by integrating local knowledge systems and practices into instruction (Mumpuni, 2022; Rosa & Orey, 2011). This approach fosters deeper engagement and helps students perceive mathematics as a meaningful and socially embedded discipline (Harding, 2022; Susanti et al., 2025).

The primary issue addressed in this study is the persistent difficulty students face in understanding geometry due to its abstract nature. Traditional didactic teaching methods often fail to support the development of students' critical thinking and spatial reasoning (Barta et al., 2022; Hitchcock, 2017; Tay & Preciado Babb, 2023). Moreover, access to high-quality technological learning tools remains limited in many educational contexts, particularly in under-resourced regions (Shamsudinova et al., 2025; Yalçin, 2023). Simultaneously, the integration of ethnomathematics into formal curricula poses challenges due to the diversity of cultural contexts and the limited availability of culturally relevant instructional materials (Kyeremeh et al., 2025; Sunzuma & Maharaj, 2021; Wulandari et al., 2024).

A general solution to these challenges involves the development of learning environments that leverage both technological innovation and cultural contextualization. Specifically, combining VR/AR technologies with ethnomathematics content offers a unique opportunity to present abstract mathematical concepts in a visually engaging and culturally meaningful manner. This dual approach aims to address both cognitive and affective barriers to learning by making geometry more accessible and relevant to diverse student populations.

Numerous studies have documented the effectiveness of VR and AR in improving mathematics learning. For example, Su, Cheng, and Lai (2022) designed a VR-based geometry system that significantly enhanced students' motivation and comprehension. Hsu (2002) and Ibáñez et al. (2020) also found that immersive environments facilitated better understanding of spatial relationships. Complementing these technological advancements, research in ethnomathematics has highlighted its role in contextualizing abstract concepts. Rosa and Orey (2011) emphasized that connecting mathematics to cultural practices can deepen students' conceptual grasp and foster a more inclusive educational experience. Moreover, Jamil et al. (2023), Kiourexidou et al. (2024), and Marín-Rodriguez et al. (2023) demonstrated that AR applications can enrich the learning environment by making abstract concepts tangible.

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Despite the progress achieved through these innovations, significant gaps still exist in how VR/AR and ethnomathematics are combined in standard classroom practices. Very few studies have examined the joint effect of these two approaches on enhancing students' critical thinking in geometry (Alves et al., 2017; Sarkar et al., 2020). Moreover, many existing implementations fail to consider the practical limitations faced by schools that lack adequate technological infrastructure (Hermawan et al., 2018; Supardi et al., 2024). There is also a lack of sufficient empirical research on how well VR/AR tools with ethnomathematical content can be scaled and adapted across different cultural settings (Kargas & Loumos, 2023; Sudirman et al., 2020).

The current study seeks to bridge these gaps by investigating the effectiveness of a VR/AR-based ethnomathematics learning model in improving students' mathematical critical thinking, particularly in geometry. This research builds on previous findings by proposing a holistic instructional framework that merges immersive technology with culturally relevant pedagogy. The innovation of this study lies in its simultaneous emphasis on cognitive development, motivational enhancement, and cultural contextualization within the geometry curriculum. By focusing on students at a university with limited resources, this research also provides insight into the practical implementation of advanced educational technologies in diverse educational environments.

Ultimately, this research aims to contribute to the development of more effective, engaging, and inclusive mathematics instruction. By offering empirical evidence on the integration of VR/AR and ethnomathematics, the study supports the advancement of educational practices that address both the abstract nature of geometry and the socio-cultural backgrounds of learners. The scope of this study includes the design, implementation, and evaluation of a VR/AR-based learning model for middle school students, with an emphasis on critical thinking in geometry. The findings are expected to inform future educational innovations that leverage technology and culture to enhance mathematics learning outcomes.

2. METHOD

This study adopted a mixed-methods approach combining Research and Development (R&D) with a quasi-experimental design to address the research objectives effectively. The primary aim was to develop Virtual Reality (VR)-based learning media and evaluate its effectiveness in enhancing students' mathematical critical thinking skills, specifically within the domain of Analytical Geometry. The choice of mixed-methods design was driven by the need to both construct a viable educational product and assess its pedagogical impact, aligning with the suggestions of Creswell and Plano Clark (2018) regarding the integration of quantitative and qualitative methodologies in educational research. The study was conducted within the Mathematics Education Study Program at UIN KHAS Jember during the 2023/2024 academic year.

The development of the VR-based learning media followed the ADDIE model, which includes the phases of Analysis, Design, Development, Implementation, and Evaluation. This model is widely accepted in instructional design for its systematic and iterative structure (Molenda, 2003). During the Analysis phase, the researchers identified students' learning difficulties in Analytical Geometry and the potential role of VR in addressing these challenges. In the Design phase, learning objectives and instructional strategies were formulated to integrate ethnomathematical content and critical thinking components. The Development phase involved the creation of the VR media, incorporating interactive elements aligned with cultural contexts and mathematical abstractions. Expert validation was conducted to ensure the appropriateness and feasibility of the product. Three content experts, three media experts, and three instructional design experts reviewed the learning media for accuracy, technical quality, and instructional design integrity. The Implementation phase included one-on-one trials with five students and small-group trials with thirteen students to identify usability issues and collect formative feedback. The Evaluation phase focused on assessing the effectiveness of the developed media through experimental research.

Following the development phase, the study employed a quasi-experimental design using a pretest-posttest control group format. This design is appropriate when random assignment is not feasible, yet control over internal validity must be maintained (Fraenkel et al., 2012). The experimental group, consisting of 37 students, received instruction using the developed VR-based media, while the control group of 34 students followed conventional teaching methods. This setup allowed for a comparative analysis of learning outcomes between the two groups.

The participants in both the development and experimental phases were undergraduate students enrolled in the Mathematics Education Study Program at State Islamic University Kiai Haji Achmad Siddiq Jember. Participation was voluntary, and ethical procedures were followed, including informed consent and data anonymization. A total of 89 students participated in the study, with five involved in one-on-one trials, thirteen in small-group trials, and the remainder in the experimental or control groups.

Multiple instruments were used to collect comprehensive data. Validation sheets were employed during the expert review process to assess content, media, and instructional quality. Pretest and posttest instruments measured students' mathematical critical thinking skills, focusing on interpretation, analysis, evaluation, inference, and explanation, as adapted from Facione (1990). Student perceptions and experiences were gathered using structured questionnaires and open-ended items. Additionally, observation sheets were utilized during trials to document student interactions with the VR media and note any technical or instructional issues. These diverse data sources allowed for triangulation and strengthened the credibility of the findings.

Quantitative data analysis was carried out using IBM SPSS Statistics 25. The analysis included normality testing via the Shapiro-Wilk test to determine the appropriate statistical tests for hypothesis testing. Depending on the results of the normality tests, the Paired Sample t-test or Wilcoxon Signed Rank Test was used to examine differences between pretest and posttest scores within groups. To measure the effectiveness of the intervention, N-Gain scores were calculated to assess learning improvements from pretest to posttest. The gain scores were interpreted based on Hake's (1999) classification, which categorized scores as high ($g \geq 0.7$), medium ($0.3 \leq g < 0.7$), and low ($g < 0.3$). Table 1 below illustrates the N-Gain classification:

Table 1 N-Gain score categorized.

Percentage	categories
$\boldsymbol{g \geq 0,7}$	Tinggi
$\boldsymbol{0,3 \leq g < 0,7}$	Sedang
$\boldsymbol{g < 0,3}$	Rendah

Qualitative data derived from observations and open-ended questionnaire responses were analyzed thematically. This approach involved coding the data to identify recurring themes related to usability, engagement, cultural relevance, and instructional impact. Themes were compared and refined through iterative analysis, enhancing the validity of interpretations (Braun & Clarke, 2006).

Ethical procedures were rigorously followed throughout the research process. Participation was voluntary, and all respondents provided informed consent before data collection. To ensure confidentiality, data were anonymized, and identifying information was removed. Ethical clearance for the study was obtained from the institutional review board of UIN KHAS Jember, confirming adherence to research ethics standards in human-subjects research.

3. RESULTS AND DISCUSSION

The results of this study demonstrate the successful development and implementation of Virtual Reality (VR)-based learning media designed to enhance students' mathematical critical thinking skills in the field of Analytical Geometry. This section presents findings from each phase of the ADDIE model, including analysis, design, development, implementation, and evaluation. These findings are supported by empirical data and are aligned with relevant literature.

3.1 Analysis Stage

Students experience a considerable level of difficulty in understanding Analytical Geometry material, with an average score of 4.16. These difficulties are mainly related to grasping basic concepts, visualizing three-dimensional shapes, and mastering topics such as the distance from a point to a plane and equations of lines in three-dimensional space. Furthermore, the conventional teaching methods used so far, such as lectures, are considered insufficient in helping students deeply understand the material.

In response to these challenges, students express a strong need for more interactive and visual learning methods, with an average score of 4.42. They highly anticipate the use of Virtual Reality (VR) technology as a learning medium that can provide a more immersive learning experience and facilitate the understanding of abstract and complex concepts. This need is supported by students' high interest in VR-based learning media and their expectation that such media can increase learning motivation.

Regarding the features of VR-based learning media, students desire several key functionalities with an average score of 4.35. The most expected features include clear three-dimensional visualization, interactive simulations, easy navigation, curriculum-aligned content, interactive exercises, clear voice guidance, multi-device accessibility, and automatic feedback during the learning process. Collectively, these expectations emphasize that the designed VR-based learning media must effectively meet learning needs and support comprehensive exploration of Analytical Geometry material.

Table 1. Average Scores of VR Learning Media Needs

Aspect	Average Score (1-5)
Difficulty in Understanding Material	4.16
Need for Interactive & Visual Methods	4.42
Desired Features of VR Learning Media	4.35

3.2 Design Stage

In the design phase, the research team selected specific software tools suitable for developing VR content, including Assembler, Canva, and GeoGebra. Each software application was chosen based on its compatibility with 3D content creation, mathematical modeling, and visual presentation. The use of GeoGebra, in particular, supported accurate rendering of geometric figures, enabling learners to manipulate and observe complex structures interactively. In addition to software selection, the mathematical content incorporated into the media focused on key topics of analytical geometry such as plane equations, lines in three-dimensional space, and distance relationships. Furthermore, ethnomathematical elements were identified by analyzing cultural patterns and spatial structures from local traditions, and these cultural representations were integrated into the 3D VR environment to support culturally meaningful understanding of geometric concepts. This selection process follows recommendations from Su, Cheng, and Lai (2022), who emphasized the importance of using reliable technological tools to facilitate meaningful learning experiences in VR environments.

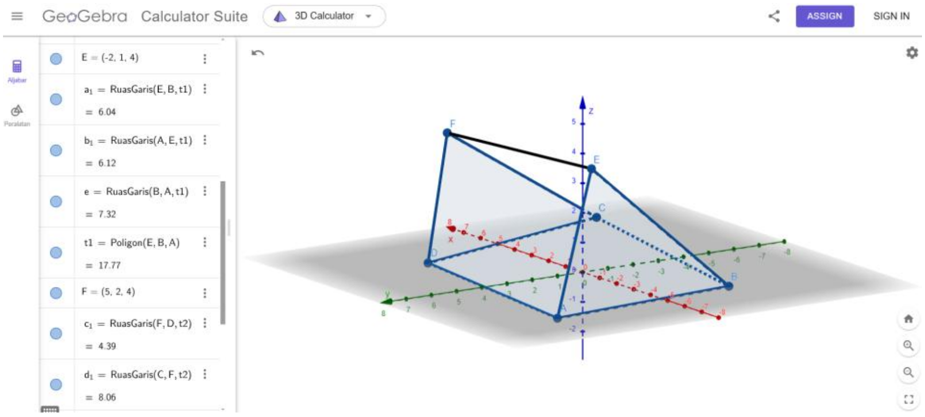


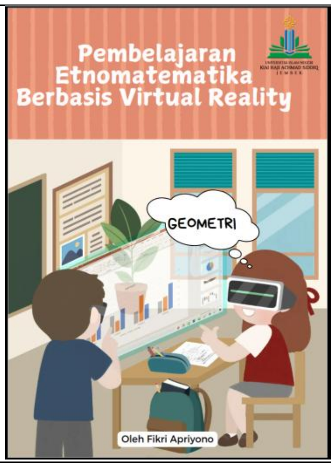
Figure 1. Geogebra Application

3.3 Development Stage

3.3.1. Product Development

The development phase produced a comprehensive VR-based learning application that included several components: a welcome interface, instructional guidelines, content navigation features, and modules covering four primary analytical geometry topics: plane equations in normal form, equations of lines in R3, the distance from a point to a plane, and the distance between two points in R3. The product design prioritized user-centered interaction and contextual relevance through immersive visualization and integration of ethnomathematical elements. These design choices are in line with the pedagogical principles proposed by Rosa and Orey (2011) regarding culturally responsive mathematics instruction.

Table 2. Product Development

No	Parts	Picture
1	Cover	

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<td>2</td>
<td>Introduction and purpose</td>
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<td>3</td>
<td>- Specification and installation
- Navigation and learning content</td>
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<td>4</td>
<td>Interaction and learning experience</td>
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<tr>
<td>5</td>
<td>Analytic geometry (plane equations in Normal Form)</td>
<td>
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<tr>
<td>6</td>
<td>Analytic geometry (equation of a line in the plane R3)</td>
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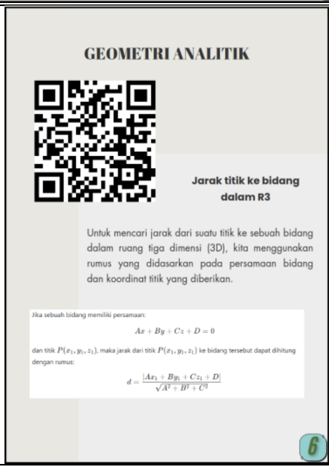
<tr>
<td>7</td>
<td>Analytic geometry (distance of a point to a plane in R3)</td>
<td>
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8	Analytic geometry (distance of two points in R3)	
9	Researcher Identity	

3.3.2. Validation Results

The Virtual Reality (VR)-based digital learning media for Analytical Geometry underwent expert validation involving three specialists who assessed test instruments—including nine essay questions targeting mathematical critical thinking—and non-test tools such as interviews, questionnaires, and checklists for media and instructional design evaluation. Using a 5-point Likert scale, results were converted into Respondent Achievement Level (TCR) percentages to gauge quality, with content experts rating alignment with learning objectives, clarity, and critical thinking development at an overall TCR of 85.93%, digital media experts evaluating usability, visual appropriateness, structure, and user comfort at 85.10%, and learning design experts reporting high interactivity, delivery effectiveness, and curriculum alignment scores totaling 88.89%. Additionally, Content Validity Ratio (CVR) and Content Validity Index (CVI) analyses confirmed good to excellent validity for most test items, with an overall CVI above 0.70. Collectively, these findings demonstrate that the VR-based learning media and its supporting instruments meet rigorous quality standards, effectively facilitating the learning process in Analytical Geometry. These findings corroborate the importance of iterative expert review in technology-enhanced instructional design, as outlined by Elamrani and Moughit (2024).

Table 3. Summary of Content Validity Ratio (CVR) and Content Validity Index (CVI) for Test Items

tem Number	Content Validity Ratio (CVR)	Category	Content Validity Index (CVI)	Category
1	1.00	Highly Appropriate		
2	1.00	Highly Appropriate		
3	1.00	Highly Appropriate		
4	0.33	Appropriate		
5	1.00	Highly Appropriate	0.776667	Highly Appropriate
6	0.33	Appropriate		
7	1.00	Highly Appropriate		
8	1.00	Highly Appropriate		
9	0.33	Appropriate		

Student trials further confirmed the media's effectiveness. One-on-one trials with five students and small-group trials with thirteen students revealed high usability and engagement. The average student response score across key dimensions (navigation ease, technical readiness, and operability) was 4.22, highlighting the product's practicality and appeal in real classroom settings.

3.4 Stages of Implementation

3.4.1. One-on-One Test

Results from the one-on-one tests showed positive reception among users. The average score for ease of navigation and product operations was 4.15, while overall usability scored 4.12 and technical readiness 4.05. All aspects fell within the "good" category. These findings suggest that students found the application intuitive and functional. However, there is still room for refinement, particularly in optimizing technical performance and enhancing user interaction feedback.

Table 4. Summary of Student Responses on Product Usability Survey

No	Aspect	Average Score	Category
1	Ease of Navigation	4.15	Good
2	Technical Readiness	4.05	Good
3	Product Operation	4.15	Good
	Overall	4.12	Good

3.4.2. Group Test

In the group trial with thirteen students, the VR-based learning product achieved an overall average score of 4.22, falling under the "very good" category. This confirmed the product's robustness across multiple users and different learning contexts. Despite its generally high ratings, further development is needed to address minor operational issues, such as response lag or device compatibility.

In terms of learning gains, the pretest score averaged 5.30, which increased to 7.11 post-intervention. The corresponding N-Gain score was 0.39, categorized as "medium." This suggests a significant but moderate improvement in students' understanding of analytical geometry following exposure to the VR-based instruction. These results are consistent with prior research (Hsu, 2002; Ibáñez et al., 2020) highlighting the impact of immersive technologies on conceptual comprehension and motivation.

3.4.3. Field Test

The field test involved a quasi-experimental design comparing outcomes between an experimental group (n = 37) using the VR media and a control group (n = 34) using traditional methods. In the experimental group, the average pretest score was 5.16 and the posttest average was 8.43, yielding a learning gain of 3.27 points. The calculated N-Gain was 0.68, classified as "medium-high."

In contrast, the control group's average pretest score was 5.26 and the posttest average was 8.17, resulting in a 2.91-point gain and an N-Gain of 0.61 (also "medium"). While both groups improved, the experimental group exhibited a higher increase, reinforcing the positive influence of VR-based learning media. This finding supports Vashisht (2024) and Marín-Rodriguez et al. (2023), who advocate for immersive technologies in enhancing mathematical reasoning and critical thinking.

3.5 Evaluation Stage

Evaluation of learning outcomes indicated that the VR-based media effectively enhanced students' mathematical critical thinking skills. The experimental group's N-Gain of 0.68 outperformed the control group and approached the high category. Students responded favorably to the product's navigational simplicity, visual clarity, and interactive features, which facilitated the visualization of complex geometric ideas and motivated engagement. These features reflect constructivist learning principles (Piaget, 1952) emphasizing the value of hands-on, experiential learning.

Moreover, the incorporation of ethnomathematics principles allowed students to contextualize geometry concepts within their cultural frameworks. This approach not only increased motivation but also made learning more meaningful and connected to real-world applications, as supported by Harding (2022) and Susanti et al. (2025). For example, the VR media used culturally familiar geometric patterns and spatial relationships to illustrate abstract mathematical ideas.

Nevertheless, the study acknowledges several limitations. The observed learning gains, while significant, remained within the medium range, indicating potential for further improvement in content design and feedback mechanisms. Technical limitations, such as the requirement for specific VR hardware, could hinder broader adoption. To address this, future iterations of the media should be optimized for mobile platforms and include diverse practice modules with automated feedback to accommodate varied learning preferences.

Overall, the findings underscore the practical and pedagogical value of integrating VR technology with ethnomathematics in mathematics education. This combination provides a powerful tool for improving critical thinking and making abstract concepts more accessible. The study contributes to the growing body of evidence supporting immersive learning technologies and culturally responsive pedagogy, pointing the way toward more inclusive and effective STEM instruction.

Discussion

The present study investigated the impact of Virtual Reality (VR) and ethnomathematics integration on improving students' mathematical critical thinking skills, specifically within the context of analytical geometry. By employing a mixed-methods approach, this research has contributed valuable insights into the effectiveness of immersive technologies in enhancing geometry education. The following discussion reflects on the main findings, their implications, and how they align with or challenge existing literature, as well as suggests possible avenues for future research.

The Impact of VR on Students' Mathematical Critical Thinking Skills

The results of this study indicate that VR-based learning significantly enhances students' mathematical critical thinking, especially in analytical geometry. The improvement in the experimental group's posttest scores, with a higher N-Gain score (0.68) compared to the control group (0.61), suggests that immersive learning technologies such as VR can play a crucial role in improving spatial reasoning and critical thinking in mathematics. These findings are consistent with the work of previous researchers who have highlighted the potential of VR and AR to improve student motivation, engagement, and learning outcomes in mathematics (Kononov et al., 2025; Vashisht, 2024). The ability of VR to provide an interactive and visually engaging experience is a key factor in this success. By presenting abstract mathematical concepts in a three-dimensional environment, VR offers students the opportunity to engage with complex ideas in a tangible and intuitive manner (Elamrani & Moughit, 2024). This approach allows for a deeper understanding of spatial relationships in geometry, which can be particularly difficult to grasp through traditional teaching methods (Iwano et al., 2021). The immersive nature of VR also helps to bridge the gap between theoretical knowledge and real-world application, thus fostering a more comprehensive and critical approach to problem-solving. Furthermore, the positive student feedback regarding the ease of navigation and technical readiness of the VR product (with an average score of 4.22) supports the idea that the technological tools were not only effective but also practical and accessible. This is crucial, as the success of educational technologies in real-world settings often hinges on their usability and stability (Su et al., 2022).

The Role of Ethnomathematics in Enhancing Student Engagement

Incorporating ethnomathematics into VR-based learning has shown to be an effective strategy for enhancing student motivation and engagement. By connecting geometry concepts to local culture, students are able to see the relevance of abstract mathematical concepts to their own lives. This culturally relevant approach helps students to view mathematics not as a foreign or irrelevant subject, but as a tool that is deeply connected to their own communities and experiences (Harding, 2022; Susanti et al., 2025). This cultural contextualization supports the development of positive learning experiences by helping students recognize that mathematics is embedded within their own traditions and environment. Incorporating local knowledge systems into geometry instruction also promotes a more holistic understanding of concepts, as highlighted by Rosa and Orey (2011), who found that bridging culture and mathematics deepens conceptual comprehension. In this study, the inclusion of ethnomathematical elements in the VR-based media aimed to make learning more meaningful and relevant to students' cultural and social backgrounds, thereby supporting stronger engagement with analytical geometry content.

The Significance of the Validation and Testing Phases

The validation process, which involved multiple experts in content, media, and instructional design, provided evidence that the VR-based learning product met the necessary quality standards. The high validation scores (85.93% for material experts, 85.10% for media experts, and 88.89% for learning design experts) reinforce the credibility of the product, suggesting that it was both pedagogically sound and technically effective. These results are aligned with studies that emphasize the importance of expert validation in the development of educational technologies, which ensures that the learning tools are both effective and appropriate for the intended educational contexts (Mumpuni, 2022; Korenova et al., 2024). The product's success was further demonstrated in the one-on-one and group testing phases, where students gave positive feedback regarding the product's ease of navigation, technical stability, and overall usability. The group test results, showing a significant increase in students' test scores (with a posttest average of 7.11 compared to a pretest average of 5.30), further validate the effectiveness of the VR-based learning environment. However, it is worth noting that while the increase in student performance was positive, the N-Gain score of 0.39 in the group test

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categorized as "medium" suggests that there is still room for improvement in the design and delivery of the VR learning experience. As such, future iterations of the product could focus on optimizing content delivery and increasing interactivity to further enhance student engagement and learning outcomes.

Implications for Educational Practices

The findings of this study suggest that VR-based learning products can be effective tools for improving students' mathematical critical thinking skills. This is especially significant in subjects like geometry, where spatial reasoning and visualization are crucial. By integrating VR with ethnomathematics, this research also demonstrates the importance of considering the cultural and contextual relevance of the content. This dual approach—leveraging advanced technology and cultural contextualization—can provide a more inclusive and engaging learning experience, which can be particularly beneficial for students from diverse cultural backgrounds. The study contributes to the growing body of research advocating for the use of immersive technologies in education, particularly in the field of mathematics. As the demand for innovative teaching methods continues to rise, educators and policymakers should consider adopting VR-based pedagogical tools that integrate cultural relevance to address both cognitive and affective challenges in mathematics education. However, as noted in the results, there are limitations, particularly in terms of accessibility and technical requirements. The reliance on VR devices with high system requirements may limit the widespread implementation of such learning tools, particularly in under-resourced schools. Future research could explore the development of more accessible VR platforms, perhaps leveraging mobile devices, to make these technologies more widely available.

Limitations and Future Research Directions

Despite the promising results, this study has several limitations that should be addressed in future research. One limitation is the sample size, which, while sufficient for the purposes of this study, may not fully capture the diversity of student learning experiences. Future studies could involve larger and more diverse student populations to assess the generalizability of the findings. Additionally, while the study focused on secondary school students in a specific geographic region, it would be valuable to examine the effectiveness of VR-based ethnomathematics learning in different educational contexts, such as in primary education or in schools with varying levels of technological access. Another area for future research is the exploration of different pedagogical models that integrate VR and ethnomathematics. While this study emphasized critical thinking in geometry, similar approaches could be applied to other areas of mathematics or even other subjects altogether. Furthermore, researchers could investigate the long-term effects of VR-based learning on students' mathematical skills and attitudes toward the subject. Finally, exploring the scalability of VR-based learning tools, especially in resource-limited environments, will be crucial to making these technologies accessible to a broader audience.

4. CONCLUSION

 This study concludes that Virtual Reality (VR)-based ethnomathematics learning media significantly enhance students' critical thinking skills in analytical geometry. The empirical findings demonstrate that the experimental group, which used VR media, achieved higher post-test scores and greater learning gains compared to the control group using conventional instruction. The medium-level N-Gain value of 0.68 in the experimental class, compared to 0.61

in the control group, confirms the added value of immersive learning environments in understanding abstract mathematical concepts. Student responses also indicate high levels of engagement, satisfaction, and ease of use, underscoring the potential of VR tools to improve both cognitive and affective learning outcomes.

The integration of ethnomathematical content into the VR environment contributed to contextualizing mathematical concepts, making them more relevant and meaningful to learners. This aligns with constructivist learning theories that emphasize experiential and culturally situated learning. Despite its effectiveness, the study also identifies limitations, particularly in terms of technical accessibility and the moderate improvement level, suggesting the need for further refinement and broader implementation studies. Future research should explore device-independent VR solutions, extend testing to diverse educational contexts, and investigate long-term impacts on learning retention and cultural engagement.

Overall, this study contributes to the growing body of knowledge supporting the integration of immersive technology and culturally responsive pedagogy in STEM education. It offers a replicable framework for educators and researchers aiming to enhance mathematics learning through innovative, engaging, and inclusive strategies.

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