



## Integrating ethnomathematics with ai-driven and ar-enhanced mathematics learning to foster critical thinking skills

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### Abstract

**Background:** Empirical evidence indicates that junior high school students' critical thinking skills in mathematics remain suboptimal, with national assessments highlighting gaps in analysis and evaluation competencies. Traditional teaching methods fail to address these higher-order thinking demands effectively.

**Aims:** This study investigates the effectiveness of an integrated learning model combining Ethnomathematics, Augmented Reality (AR), Artificial Intelligence (AI), and Deep Learning (DL) in enhancing students' critical thinking skills in mathematics.

**Method:** A mixed-method sequential explanatory design was employed. The quantitative phase used a quasi-experimental one-group pretest-posttest design with 64 junior high school students in Purworejo, Indonesia. The qualitative phase included semi-structured interviews, focus group discussions, and classroom observations. Critical thinking was measured using a validated 10-item test (Cronbach's  $\alpha = 0.82$ ). The intervention lasted four weeks (12 sessions of 80 minutes).

**Results:** The quantitative phase showed significant improvement in critical thinking scores ( $t = 4.126$ ,  $p < 0.001$ , 95% CI [18.2, 27.8]) with a high N-Gain of 73% (Cohen's  $d = 0.58$ ). Interpretation and evaluation indicators exhibited the highest gains (N-Gain 0.76–0.77). Qualitative findings revealed positive student engagement (mean 4.6/5) and cultural relevance (mean 4.5/5), while teachers found the model innovative but noted infrastructure and training challenges.

**Conclusion:** The integrated Ethno-AR-AI-DL model effectively improves critical thinking and is positively perceived by users. These findings suggest the potential of culturally relevant, technology-enhanced mathematics instruction, provided teacher training and infrastructure are addressed.

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## INTRODUCTION

International assessments such as PISA 2022 reported that Indonesian students' mathematical literacy averaged 366, significantly below the OECD average of 472, with fewer than 2% reaching proficiency levels requiring critical thinking (Fauzi et al., 2025; OECD, 2023). Nationally, minimum competency assessments (AKM) indicate that only 34% of junior high school students demonstrate adequate analytical reasoning in mathematics (Susanto et al., 2022). These empirical gaps justify the urgency of pedagogical innovation targeting critical thinking. Critical thinking is a fundamental 21st-century skill that empowers students to analyze information, make decisions, and solve problems (Acosta-Gonzaga, 2023; Cananau et al., 2025; Leibovitch et al., 2025). However, conventional teaching methods often fail to foster higher-order thinking (Ndiung et al., 2024), and many teachers possess limited understanding of how to teach critical thinking explicitly (A. Putri et

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al., 2025). Therefore, improving critical thinking requires both appropriate instructional design (Yohannes et al., 2021) and adequate technological support (Zeng & Ravindran, 2025).

A growing body of literature has separately examined the benefits of each pedagogical and technological component in mathematics education. Recent studies on ethnomathematics have demonstrated that integrating local cultural artifacts such as batik, traditional architecture, and games into mathematics instruction improves conceptual understanding, critical thinking, and student motivation (Kurniawan et al., 2023; Rahayu et al., 2025; Wahyudi & Putra, 2022). Cultural objects can serve as potential learning resources (Dhiki & Bantas, 2021; Faqih et al., 2021), increasing material relevance and making learning more meaningful (Insorio & Librada, 2025). However, the mathematization process and integration of local culture present complex challenges, particularly regarding technological visualization. Augmented reality (AR) has been shown to enhance visualization of abstract mathematical concepts. AR supports constructivist learning as a transformative tool that illustrates mathematical concepts visually and interactively (Velázquez & Méndez, 2021). Recent studies confirm that AR-based learning environments improve spatial reasoning, engagement, and higher-order thinking skills (Mandala et al., 2025). By integrating the real world with interactive digital objects, AR enables students to understand abstract concepts through immersive visualization, thereby encouraging critical thinking and problem-solving. Nevertheless, the transition from conventional learning to AR-based environments remains challenging (Lai & Cheong, 2022), and the visualization of ethnomathematical objects tailored to students' needs requires further development.

Artificial intelligence (AI) and deep learning (DL) have emerged as powerful tools for personalizing mathematics instruction. AI can personalize learning through material adaptation, student profile analysis, chatbots, resource recommendations, and time management tailored to students' learning styles (Mohamad et al., 2022). AI can group students based on learning difficulties and predict performance using data on task completion duration and error rates. Deep learning techniques create artificial neural networks that learn patterns from input data while simultaneously predicting learning abilities, including task completion time, error patterns, interaction with materials, and engagement levels (Salas-Rueda et al., 2025). Recent systematic reviews confirm that DL holds promise for improving learning outcomes through predictive analytics across multiple platforms (Rizwan et al., 2025). Despite the established benefits of each component individually, no previous study has integrated all four components ethnomathematics, AR, AI, and DL within a single instructional framework aimed specifically at enhancing critical thinking. Prior research has focused on AR alone (Mandala et al., 2025), ethnomathematics with traditional methods, or AI/DL for adaptive feedback in non-cultural contexts. However, the potential synergy between cultural contextualization and personalized adaptive learning remains unexplored. This integration gap limits our understanding of how these four elements might interact to foster higher-order thinking skills.

The novelty of this study is threefold. First, it simultaneously integrates four distinct pedagogical and technological components that have previously been studied only in isolation or in pairs. Second, it develops and examines an AR-Ethnomath application that embeds AI and DL as adaptive support features rather than as standalone interventions. Third, it focuses specifically on critical thinking as the primary outcome variable within a culturally grounded mathematics context, whereas prior research has typically measured general learning outcomes or conceptual understanding. In this study, cultural objects (ethnomathematics) are presented in 3D through AR, AI provides personalized support by presenting randomized questions with varying difficulty levels and chatbot feedback, and DL analyzes student interaction data to generate teacher dashboards for learning reflection and instructional planning.

## LITERATURE REVIEW

This study is underpinned by three complementary theoretical perspectives that together justify the integration of ethnomathematics, augmented reality (AR), artificial intelligence (AI), and deep learning (DL) within a single instructional framework. Rather than treating these four components as separate add-ons, the theoretical framework explains how they synergistically support the development of critical thinking skills in mathematics.

### ***Constructivist Learning Theory: AR as a Mediator for Active Knowledge Construction***

Constructivist learning theory (Efgivia et al., 2021; Mishra, 2023) posits that learners actively construct knowledge through interaction with their environment rather than passively receiving information. In the context of this study, AR serves as a technological mediator that enables active knowledge construction by allowing students to interact with three-dimensional visualizations of cultural objects. When students scan AR markers to reveal batik patterns or joglo houses in 3D, they are not merely observing static images; they are manipulating, rotating, and exploring geometric properties from multiple perspectives. This interactivity aligns with Vygotsky's concept of the zone of proximal development, where AR provides a scaffold that helps students grasp abstract mathematical concepts (symmetry, transformation, spatial relationships) that would otherwise remain inaccessible. Thus, constructivist theory justifies the inclusion of AR as a tool for making ethnomathematical objects experientially accessible.

### ***Ethnomathematics Theory: Culture as the Content Backbone***

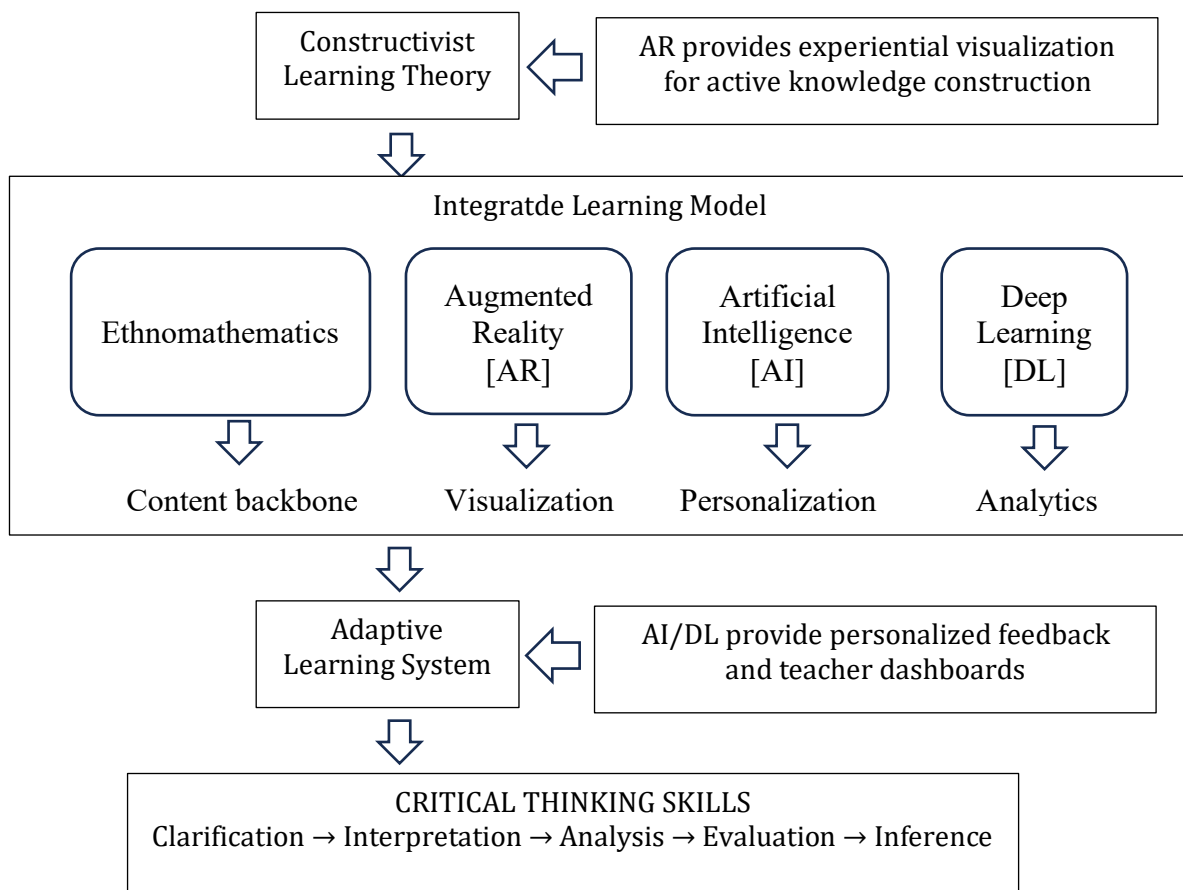
Ethnomathematics theory (Fraz et al., 2023; Rosa & Orey, 2021) argues that mathematical knowledge is culturally situated and that learning is more meaningful when mathematics is connected to learners' socio-cultural environments. In this study, ethnomathematics provides the content backbone for all learning activities. The batik patterns, traditional carvings, and joglo architecture of Purworejo are not decorative additions; they are the primary objects through which mathematical concepts are introduced, explored, and practiced. This cultural grounding serves two theoretical purposes. First, it reduces the perceived abstraction of mathematics by anchoring concepts in tangible, familiar cultural artifacts. Second, it fosters cultural pride and identity, which prior research has shown to increase student motivation and persistence. Ethnomathematics theory therefore justifies why cultural objects are not optional enhancements but essential to the instructional design.

### ***Adaptive Learning Systems Theory: AI/DL for Personalization and Feedback***

Adaptive learning systems theory (Betts et al., 2021) emphasizes that learning is optimized when instruction is tailored to individual student needs, including appropriate difficulty levels, immediate feedback, and opportunities for mastery learning. In this study, AI and DL operationalize these principles. The AI component adaptively generates question difficulty based on each student's response patterns, ensuring that students are neither bored by overly easy tasks nor frustrated by excessively difficult ones. The DL component analyzes aggregated interaction data to identify error patterns, common misconceptions, and engagement trajectories, which are then visualized in a teacher dashboard. This theoretical alignment ensures that personalization is not merely a technological feature but a pedagogically grounded mechanism for supporting critical thinking development. Importantly, adaptive learning systems theory also emphasizes that technology should augment not replace teacher judgment, which guides our implementation of AI and DL as decision-support tools rather than autonomous instructors.

### ***The Synergistic Integration: How the Four Components Work Together***

The novelty of this study lies not in the isolated application of each component but in their synergistic integration. The synergy emerges because each component addresses a different barrier to critical thinking. Ethnomathematics addresses the barrier of meaninglessness (why should I care about this math?). AR addresses the barrier of abstraction (what does this concept look like?). AI addresses the barrier of mismatched difficulty (is this too hard or too easy for me?). DL addresses the barrier of invisible progress (what am I misunderstanding?). When all four barriers are addressed simultaneously, students are more likely to engage in the higher-order thinking processes interpretation, analysis, evaluation that constitute critical thinking. Figure 1 illustrates the integration of the three theoretical perspectives and four components.



**Figure 1.** Theoretical Framework of the Ethno-AR-AI-DL Model

In summary, the Ethno-AR-AI-DL model is not a random assemblage of technologies and pedagogies. It is a theoretically grounded framework in which: (1) ethnomathematics provides culturally meaningful content, (2) constructivist theory justifies AR as a tool for active exploration, (3) adaptive learning systems theory justifies AI/DL for personalization and feedback, and (4) the synergy among all four addresses multiple barriers to critical thinking simultaneously.

## **METHOD**

### **Research Design**

This study used a mixed-methods sequential explanatory design (Ivankova et al., 2006; Nagpal et al., 2021). A mixed-methods approach was chosen because improving critical thinking requires both statistical confirmation (quantitative) and a contextual understanding of how and why the model works (qualitative). The quantitative phase (pretest–posttest) measures the magnitude of

change or improvement in students' critical thinking skills. The qualitative phase (interviews, focus group discussions, observations) explores the mechanisms underlying the observed results. Quantitative and qualitative integration occurs at the interpretation stage, where qualitative findings are used to explain quantitative results.

### Participants

The study was conducted at SMP N 4 and SMP N 12 Purworejo with participants consisting of 64 seventh grade students (28 boys, 36 girls; age range 12–14 years) and two mathematics teachers from the two schools. Purposive sampling was conducted by setting the following criteria: (1) availability of Android-based devices for AR access, (2) stable internet connectivity, (3) both schools are categorized as schools with medium abilities with the aim of avoiding extreme bias so that the findings.

### Role of AI and DL

In this study, artificial intelligence (AI) and deep learning (DL) served as supporting features within the AR-Ethnomath application, not as independent experimental variables. Specifically, the AI component adaptively presented questions of varying difficulty, recorded student response patterns, and provided analysis of each student's errors. When a student answered correctly, the AI presented a question of slightly more challenging difficulty. When a student answered incorrectly, the AI provided immediate corrective feedback via a chatbot and offered questions of similar or lower difficulty to reinforce understanding. Meanwhile, the DL component worked in the background by analyzing aggregated interaction data from all students, including response times, error patterns, engagement levels, and task completion rates. The results of this analysis were then visualized in a teacher dashboard, which provided educators with real-time information about class progress and common student misconceptions. This study emphasized that neither AI nor DL replaces the role of teachers; instead, both serve as decision-support tools that enable differentiated instruction and data-driven pedagogical reflection. The teacher remains the primary facilitator, interpreting the DL-generated dashboard and making final instructional decisions.

### Instruments

To ensure coherence between the research questions and data collection, each instrument was designed to address a specific research question (RQ). For RQ1 (effectiveness on critical thinking), the primary instrument was a critical thinking essay test administered in pre- and post-test formats. The test was validated by experts and showed a reliability coefficient of 0.82 (Cronbach's Alpha). For RQ2 (student perceptions of engagement, cultural relevance, and practicality), the primary instrument was a 1- to 5-point Likert-scale questionnaire, supplemented by focus group discussions and classroom observations to deepen qualitative insights. For RQ3 (feasibility factors and barriers identified by teachers), semi-structured interviews served as the primary instrument, with classroom observations providing triangulation. The use of these instrument formats ensured that each RQ was addressed by at least one primary instrument, with secondary instruments providing contextual depth and cross-validation.

### Intervention Procedure

The intervention lasted four weeks (12 sessions, each 80 minutes). Each session followed a consistent structure as shown in Table 1.

**Table 1.** Session structure of the Ethno-AR-AI-DL Intervention

| Phase       | Duration   | Activities  |
|-------------|------------|---|
| Orientation | 10 minutes | Teacher introduces cultural objects (batik patterns, joglo houses, traditional carvings) and states learning objectives |

|                         |            |   |
|-------------------------|------------|---|
| AR Exploration          | 25 minutes | Students scan AR markers using the AR-Ethnomath application to visualize 3D objects and identify geometric properties (symmetry, transformation, spatial relationships) |
| AI-Adaptive Practice    | 25 minutes | Students solve 5–7 randomized difficulty questions; AI adjusts difficulty based on response accuracy; chatbot provides immediate corrective feedback                    |
| DL-Supported Reflection | 10 minutes | Teacher reviews class progress dashboard (aggregated error patterns, completion times, engagement metrics) generated by DL analysis                                     |
| Closure                 | 10 minutes | Summary of key concepts, individual goal setting, and preview of next session   |

### Data Collection Procedure

Data collection was conducted in two sequential phases consistent with a mixed-methods sequential explanatory design. In the quantitative phase, students completed a 40-minute pretest to measure critical thinking skills one week before the intervention. The intervention was then administered over four weeks, consisting of 12 80-minute sessions, during which students engaged in learning with the Ethno-AR-AI-DL integration. After the intervention, the same critical thinking test was administered as a posttest to assess changes in students' critical thinking skills. The qualitative phase was conducted immediately following the posttest. Data were collected from multiple sources to capture student and teacher perceptions and the impact of contextual factors. Semi-structured interviews were conducted with two mathematics teachers (60 minutes each), and focus group discussions were conducted with 24 students divided into three equal groups for 45 minutes each. Additionally, classroom observations were conducted during four randomly selected intervention sessions to document student engagement, collaboration, and hands-on technology use. Finally, questionnaires were distributed to all students to gauge their perceptions of engagement, cultural relevance, and practicality of the learning model.

### Data Analysis

Quantitative data were analyzed using SPSS. This began with assumption testing to ensure the validity of parametric statistics. The normality of pretest and posttest scores was examined using the Shapiro–Wilk test, which indicated that both groups came from normally distributed populations (pretest  $p = 0.142$ , posttest  $p = 0.208$ ). Homogeneity of variance was measured using Levene's test ( $p = 0.312$ ), which indicated that both classes had homogeneous variances. A paired-sample t-test with a 95% confidence interval (CI) for the difference in means was then conducted to determine whether the change in critical thinking scores from pretest to posttest was statistically significant. Effect sizes were calculated using Cohen's  $d$ , which was interpreted as small ( $d \geq 0.2$ ), medium ( $d \geq 0.5$ ), or large ( $d \geq 0.8$ ). Normalized gain (N-Gain) was calculated using the formula:  $(\text{post-test score} - \text{pre-test score}) / (\text{maximum score} - \text{pre-test score})$ , with categories defined as high ( $g \geq 0.7$ ), moderate ( $0.3 \leq g < 0.7$ ), and low ( $g < 0.3$ ). Qualitative data were analyzed using thematic analysis following Braun and Clarke's (2006) six-phase framework: data familiarization, initial coding, theme generation, theme review, theme definition, and report writing. To ensure rigor and trustworthiness, inter-coder reliability was established by having a second researcher independently code 25% of the qualitative data, resulting in a Cohen's  $\kappa$  of 0.84, indicating strong agreement. Further triangulation was conducted across three data sources—teachers, students, and classroom observations—to enhance the credibility and confirmability of the qualitative findings.

## RESULTS AND DISCUSSION

## Results

**RQ 1: Improvement of Students' Critical Thinking Skills**

A paired-sample t-test was conducted to compare pretest and posttest critical thinking scores. Assumption testing confirmed normality (Shapiro–Wilk: pretest  $p = 0.142$ , posttest  $p = 0.208$ ) and homogeneity of variance (Levene's test:  $p = 0.312$ ). Table 2 presents the descriptive and inferential statistics.

**Table 2.** Pre and Post Test Result

| Measure   | N  | Mean  | SD   | Mean Difference | 95%CI        | t (df=63) | p-value | Cohen's d | N-Gain |
|-----------|----|-------|------|-----------------|--------------|-----------|---------|-----------|--------|
| Pre-test  | 64 | 55.00 | 8.20 | 23.00           | [18.2, 27.8] | 4.126     | < 0.001 | 0.58      | 0.73   |
| Post-test | 64 | 78.00 | 7.50 |                 |              |           |         |           |        |

The analysis revealed a statistically significant improvement from pretest ( $M = 55.00$ ,  $SD = 8.20$ ) to posttest ( $M = 78.00$ ,  $SD = 7.50$ ), with a mean difference of 23.00 (95% CI [18.2, 27.8]). The t-value was 4.126 ( $df = 63$ ,  $p < 0.001$ ). The effect size (Cohen's  $d = 0.58$ ) indicates a medium-to-large practical effect. The N-Gain score of 0.73 (73%) falls within the "high" category. Table 3 presents the improvement disaggregated by the five critical thinking indicators.

**Table 3.** Improvement by Critical Thinking Indicators (N = 64)

| Indicator      | Mean Pretest | Mean Posttest | Mean Gain | N-Gain | Category    |
|----------------|--------------|---------------|-----------|--------|-------------|
| Clarification  | 56           | 75            | 19        | 0.68   | Medium-High |
| Interpretation | 54           | 80            | 26        | 0.76   | High        |
| Analysis       | 55           | 77            | 22        | 0.71   | High        |
| Evaluation     | 53           | 79            | 26        | 0.77   | High        |
| Inference      | 57           | 76            | 19        | 0.67   | Medium-High |

All five indicators showed improvement. Interpretation and evaluation demonstrated the highest gains (N-Gain = 0.76 and 0.77, respectively). Clarification and inference showed N-Gain scores of 0.68 and 0.67, respectively.

**RQ2: Students' Perceptions of Engagement, Cultural Relevance, and Practicality**

Table 4 presents mean scores from the student response questionnaire (5-point Likert scale: 1 = strongly disagree, 5 = strongly agree)

**Table 4.** Student Perceptions of the Ethno-AR-AI-DL Model (N = 64)

| Aspect             | Mean Score | SD   | Category      |
|--------------------|------------|------|---------------|
| Engagement         | 4.6        | 0.52 | Very Positive |
| Cultural Relevance | 4.5        | 0.58 | Very Positive |
| Practicality       | 4.4        | 0.61 | Positive      |

Beyond the quantitative ratings, exploratory findings on teacher and student perceptions provided deeper insights into students' critical thinking learning outcomes. Data were analyzed using thematic coding: responses were transcribed, coded, and categorized into themes such as practicality, engagement, cultural relevance, adaptability, and motivation as shown in Table 5.

**Table 5.** Themes from Teacher and Student Responses

| Theme      | Evidence from Data  |
|------------|---|
| Engagement | Students more active in discussions, asked questions, collaborated frequently |

|                          |   |
|--------------------------|---|
| Motivation               | Higher interest and willingness to solve problems                   |
| Cultural Relevance       | Batik and local architecture made mathematics relatable             |
| Practicality             | Teachers found the model feasible and curriculum-aligned            |
| Innovation               | Teachers viewed the model as novel and future-oriented              |
| Clarity of Understanding | AR visualizations clarified abstract concepts                       |
| Collaboration            | Students showed stronger peer interaction and group problem-solving |
| Adaptability             | AI/DL features provided personalized feedback for learners' needs   |

Adaptive AI/DL features provided personalized feedback tailored to learners' needs. Thematic coding highlighted consistent patterns across interviews, focus group discussions, observations, and open-ended questionnaire responses. For example, students emphasized engagement: *"With AR, I can see batik patterns that directly relate to the problem — which makes me feel empowered to ask questions"* (Student, Class A). Teachers emphasized conceptual clarity: *"3D objects make concepts that are usually abstract tangible; students understand the relationships more quickly"* (Teacher 1). Both groups valued cultural relevance and adaptability, although teachers also mentioned the need for adequate training and resources to ensure sustainability. Table 6 presents supporting evidence with illustrative quotes from participants.

**Table 6.** Qualitative Themes and Supporting Evidence

| Theme                      | Supporting Evidence  | Illustrative Quotes   |
|----------------------------|--|---|
| Engagement & Participation | Increase in student questions, group discussions, collaborative problem-solving        | "With AR, I can see the batik pattern directly related to the problem — so I dare to ask questions." (Student, Class A) |
| Conceptual Clarity         | AR visualisation made abstract concepts (e.g., symmetry, geometry) more tangible       | "3D objects make normally abstract concepts tangible; students grasp the relationships faster." (Teacher 1)             |
| Cultural Relevance         | Local motifs and architecture connected mathematics with students' cultural background | "Local cultural-based content makes students feel the material is close, not just theory." (Teacher 2)                  |
| Adaptivity & Feedback      | AI/DL system provided tailored tasks and feedback                                      | "The system gives tasks that suit me; I see where I need more practice." (Observation & AI log)                         |
| Practicality / Feasibility | Feasible but requires training and resources   | "Pedagogically it fits well, but we need technical training and funding for devices." (Teacher 1)                       |
| Motivation & Attitude      | Students more motivated, positive attitudes toward learning                            | "Learning becomes fun — not boring anymore." (Student, Class B)   |

Students viewed the Ethno-AR-AI-DL model positively, highlighting its engagement, cultural relevance, and practicality as its strongest features. AR visualizations helped them grasp abstract concepts more easily. Ethnomathematics fostered a sense of pride in cultural identity, especially when integrated into lessons. The adaptability of AI/DL provided challenges that motivated persistence. Teachers perceived the model as innovative, practical, and curriculum-aligned. They noted that AR helped visualize abstract concepts, ethnomathematics made lessons culturally relevant, and AI/DL features provided adaptive feedback on student progress. Classroom observations confirmed these perceptions: students were more actively engaged, collaborated in groups, and persisted in problem-solving activities.

### RQ3: Teachers' Identification of Feasibility Factors and Barriers

Interviews with both mathematics teachers revealed their perceptions of the model, including both positive aspects and challenges.

Positive perceptions: Teacher 1 stated: "*3D objects make normally abstract concepts like symmetry tangible; students grasp the relationships faster*". Teacher 2 added: "*Local cultural-based content makes students feel the material is close to them, not just abstract theory*". However, teachers also identified significant challenges. Challenges Identified: Teacher 1 noted: "*Pedagogically it fits well, but we need technical training and funding for devices*". Teacher 2 added: "*We need more training sessions before full adoption, and devices must be available for all students, not just some*". Table 7 summarizes the main themes from teacher interviews.

**Table 7.** Teacher Evaluation Themes

| Theme                | Teacher Perceptions  |
|----------------------|--|
| Innovation           | The model introduces a novel, technology-enhanced approach to mathematics learning     |
| Curriculum Alignment | Content can be integrated with the current mathematics curriculum                      |
| Practicality         | The model is feasible for classroom use, provided adequate resources are available     |
| Challenges           | Implementation requires teacher training, stable infrastructure, and technical support |

## Discussion

This section interprets the findings presented above, compares them with prior literature, and discusses their implications. The discussion is organized according to the three research questions, followed by a dedicated sub-section on novelty and theoretical contributions. The finding that critical thinking scores improved significantly (N-Gain = 73%,  $d = 0.58$ ) suggests that the Ethno-AR-AI-DL model is associated with meaningful gains in students' critical thinking abilities. The medium effect size places this intervention in the upper-moderate range compared to meta-analyses of educational technology interventions, where effect sizes typically range from 0.2 to 0.8. This indicates that while the model is promising, its effectiveness depends on implementation quality, teacher readiness, and infrastructure reliability.

The finding that interpretation and evaluation showed the highest gains (N-Gain = 0.76 and 0.77) aligns with core critical thinking framework, where evaluative judgment benefits from adaptive feedback loops. AR's visualization of cultural objects likely reduced cognitive load, freeing cognitive resources for higher-order analysis and evaluation. The AI and DL support adaptive feedback tailored to students' needs. This is in line with study who emphasize that immersive learning strategies encourage attentive, meaningful, and reflective learning, which is crucial for developing critical thinking skills (Nafi'ah & Faruq, 2025; Taqiyya et al., 2025). Similar results stated that a mobile AR-based geometry learning game can significantly improve students' spatial reasoning skills through interactive visualization (Mandala et al., 2025) and the use of AR-assisted experiential learning resulted in higher reasoning scores compared to direct learning (Maulida et al., 2024). These studies reinforce the effectiveness of AR when integrated into mathematics learning. The high engagement rating suggests that AR visualization successfully captured student attention and sustained participation across 12 sessions. This resonates with research showing that immersive, interactive technologies increase student motivation and time-on-task (Velázquez & Méndez, 2021).

Students rated the model highly on engagement (4.6/5), cultural relevance (4.5/5), and practicality (4.4/5). These positive perceptions are consistent with constructivist perspectives emphasizing that active engagement with contextual representations fosters deeper learning. The strong cultural relevance rating supports ethnomathematics thesis that connecting mathematics to learners' socio-cultural environments increases meaningfulness and reduces the perceived abstraction of mathematical concepts (D'Ambrosio, 2006). Students explicitly mentioned that batik patterns and local architecture made mathematics "feel close" rather than "just theory." This aligns

with recent findings that culturally embedded mathematics fosters pride and identity (Rahayu et al., 2025; Rosa & Orey, 2021). Teachers perceived the model as innovative and curriculum-aligned, reflecting the TPACK framework (A. D. Putri et al., 2024; Shamim et al., 2024), which emphasizes the integration of content, pedagogy, and technology. However, teachers also emphasized significant barriers: the need for professional development, adequate device availability, stable internet connectivity, and ongoing technical support. These concerns echo broader findings that Indonesian teachers value technology integration but often lack adequate training and resources (Sutarto et al., 2020). Equitable access to digital infrastructure remains a global challenge in educational technology adoption (Lai & Cheong, 2022). Despite these challenges, teacher optimism suggests high potential for scaling the model with appropriate support. Teacher acceptance of technology is closely linked to perceived feasibility and institutional support.

This study offers several novel contributions that distinguish it from prior research and address the gaps identified in the literature. What makes this study different? While previous studies have separately examined ethnomathematics, AR, or AI/DL in mathematics education, no prior study has integrated all four components within a single instructional framework. The present study demonstrates that these components are not only compatible but potentially synergistic. The finding that interpretation and evaluation the two highest-order critical thinking indicators showed the greatest gains suggests that the integration of cultural contextualization (ethnomathematics) with adaptive feedback (AI/DL) and immersive visualization (AR) may be particularly effective for fostering complex reasoning skills, rather than merely basic comprehension. Culturally grounded adaptive learning. This study provides empirical evidence for what might be termed "culturally grounded adaptive learning"—a concept not previously documented in the literature. Prior adaptive learning systems have typically been culturally neutral, while ethnomathematics interventions have rarely incorporated AI-driven personalization. The present study shows that cultural artifacts (batik, joglo houses) can serve as the content backbone for AI-adaptive questioning, and that students respond positively to this combination. The high cultural relevance rating (4.5/5) suggests that students did not perceive technology as detracting from cultural authenticity; rather, AR and AI amplified their engagement with local heritage.

This study contributes to the ongoing debate about the role of AI in education by positioning AI and DL as teacher-support tools rather than autonomous instructors. The teacher dashboard generated by DL analysis was perceived by teachers as useful for differentiated instruction, but teachers also emphasized that they remained the primary decision-makers. This finding addresses concerns raised in recent literature about AI replacing teachers and instead supports a model of augmented teaching where AI enhances rather than supplants professional judgment. This study extends constructivist learning theory by demonstrating that AR-enabled visualization of cultural objects supports active knowledge construction in ways that static cultural artifacts cannot. It also operationalizes ethnomathematics framework within a technology-enhanced environment, showing that digital tools can amplify rather than replace cultural grounding. The findings suggest that the Ethno-AR-AI-DL model is not only effective but also feasible, provided that adequate teacher training and infrastructure support are in place. Schools and policymakers should therefore view technology integration not as a replacement for cultural pedagogy but as a complement that can make culturally grounded mathematics more engaging and adaptive to individual student needs.

### Implications

The implications of this study suggest that integrating Ethnomathematics with Augmented Reality (AR), Artificial Intelligence (AI), and Deep Learning (DL) can significantly enhance critical thinking in junior high school students. The findings demonstrate the synergy between these components, addressing various barriers to critical thinking. Ethnomathematics provides a culturally

relevant content foundation, making mathematical concepts more meaningful and relatable to students. The AR feature supports active knowledge construction, allowing students to interact with visual representations of mathematical concepts that would otherwise be abstract. AI and DL personalize the learning experience by adapting content difficulty to individual student needs, providing real-time feedback, and analyzing student progress to guide instructional decisions. This personalized approach ensures that students are engaged and appropriately challenged, fostering deeper critical thinking. However, successful implementation of this integrated model requires addressing challenges related to teacher training, infrastructure, and resource availability. Teachers need adequate support to effectively incorporate technology, ensuring that these tools are not merely supplementary but central to the learning experience. Additionally, equitable access to devices and stable internet connectivity is essential for scaling this model across diverse educational settings. This study also emphasizes the importance of integrating cultural contexts into mathematics education, as it enhances student engagement and fosters a sense of identity and belonging, which in turn motivates them to engage more deeply with the content. Therefore, for long-term success, schools must invest in both professional development for teachers and the necessary technological infrastructure.

### **Limitations and Suggestions for Future Research**

The limitations of this study primarily arise from the absence of a control group, which hinders the ability to make causal inferences about the effectiveness of the integrated Ethno-AR-AI-DL model. Additionally, the sample size of 64 students from two schools in one district limits the generalizability of the findings to broader populations. The relatively short intervention period of four weeks may not fully capture the long-term impact of the model on students' critical thinking skills, and future studies should extend the duration to assess sustained effects. Moreover, the AI and DL components were implemented as supporting features within a comprehensive system, and their potential effects as standalone interventions were not explored. Further research should incorporate a control group to strengthen causal conclusions and expand the sample size to include a more diverse student population. Investigating the long-term retention of critical thinking skills after the intervention would provide deeper insights into the lasting impact of the integrated model. Moreover, exploring alternative technologies, such as virtual reality (VR), could enhance the cultural learning experience by offering a more immersive and authentic environment. Additionally, expanding the range of cultural artifacts and mathematical competencies assessed could provide a more comprehensive understanding of the model's effectiveness. Future studies should also explore how teacher professional development and the availability of technological resources influence the implementation and success of such models in different educational contexts. Further examination of the interaction between cultural relevance and technological tools will help refine pedagogical approaches and make mathematics learning more accessible. Lastly, the role of teacher feedback in shaping the learning experience should be examined in greater detail to understand its contribution to the overall success of the model. Finally, the integration of more varied mathematical skills, beyond critical thinking, such as problem-solving and quantitative literacy, should be considered for a holistic assessment of the model's impact.

### **CONCLUSION**

This study demonstrates that integrating ethnomathematics, augmented reality (AR), artificial intelligence (AI), and deep learning (DL) within a single learning framework can improve critical thinking skills in junior high school students. Quantitative analysis revealed a significant increase in critical thinking scores (N-Gain = 73%, Cohen's  $d = 0.58$ ), particularly in the interpretation

and evaluation indicators, which showed the highest improvement. Qualitative data indicated students had positive perceptions of their engagement in learning (score 4.6) and understanding of the cultural relevance of mathematics (score 4.5). Furthermore, teachers viewed the AR-AI-Ethno and deep learning integration as innovative and aligned with the current mathematics curriculum, although they emphasized the importance of training and the readiness of supporting AR infrastructure. This study must be acknowledged as having several limitations. The lack of a control group limits causal inference, while the sample size of only 64 students from two schools in one district may limit the generalizability of the results to a broader population. The AI and DL components were implemented as supporting features of a fully autonomous system, so their potential effects may not be optimal. Furthermore, the four-week intervention duration is relatively short for measuring sustained change, and the study did not measure the long-term impact of improved critical thinking skills. Theoretically, this study extends constructivist learning theory by demonstrating how AR-assisted visualization of cultural objects supports the active construction of knowledge in mathematics. It also operationalizes a technology-enabled ethnomathematics approach, demonstrating that cultural foundations can be strengthened by digital tools, while providing empirical evidence of the synergistic potential of combining adaptive learning systems with culturally contextualized instruction.

### AUTHOR CONTRIBUTIONS STATEMENT

Heru Kurniawan was responsible for conceptualizing the research framework, designing the Ethno-AR-AI-DL instructional model, coordinating data collection in the classroom, and drafting the manuscript. Nila Kurniasih contributed to the implementation of the intervention, conducted classroom observations, facilitated focus group discussions, and supported data analysis. Both authors participated in developing the theoretical framework, validating research instruments, interpreting findings, and refining the instructional design. Additionally, they collaborated in reviewing and finalizing the manuscript, ensuring accuracy, clarity, and coherence. Both authors actively discussed the results, reviewed the qualitative and quantitative analyses, and approved the final version of the manuscript. They agreed to be accountable for all aspects of the research, including the integrity of data and conclusions drawn from the study.

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