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Integrating Local Genius Mabbelle and Augmented Reality to Foster Metacognitive Skills in Mathematics Learning

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Abstract

Metacognitive skills are essential competencies for supporting higher-order thinking and self-regulated learning; however, their development among Indonesian students remains limited. This study aims to develop and evaluate an Augmented Reality (AR)-based learning media integrated with the Local Genius Mabbelle, a traditional Bugis game, to enhance students' metacognitive skills while strengthening collaborative learning and cultural awareness. The study employed a Research and Development approach using the ADDIE model involving mathematics teachers and seventh-grade students at SMP Negeri 1 Kahu, Indonesia. Data were collected through observations, interviews, questionnaires, validation sheets, and pretest-posttest assessments. The findings indicate that the developed Mabbelle-AR media is highly valid, with average validation scores of 3.72 from material experts, 3.85 from design experts, and 3.58 from media experts. Practicality testing showed very positive responses from both teachers and students. The effectiveness test revealed that the experimental class achieved a higher N-Gain score (45.16; 70%) than the control class (22.97; 47%). Further analysis demonstrated substantial improvements in metacognitive components, including planning, monitoring, evaluation, and self-regulation. The implementation also strengthened collaborative learning, increased learning motivation and engagement, promoted digital literacy and problem-solving skills, and facilitated the internalization of Bugis cultural values such as *Sipakatau*, *Sipakalebbi*, and *Lempu*. The novelty of this study lies in the integration of culturally embedded local wisdom with AR technology to create a contextual, immersive, and metacognition-oriented learning environment. This approach offers an innovative model for mathematics education that simultaneously promotes cognitive development, cultural preservation, and quality education.

Keywords: augmented reality learning, higher order thinking skills, innovative learning design, local wisdom-based education, metacognition skills, progressive mathematics education.

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1. Introduction

Metacognition skills are fundamental elements that play a crucial role in problem-solving and the transfer of cognitive skills. These skills are integrated into eight essential pillars that underpin cognitive and psy-

chophysiological mechanisms, significantly contributing to the optimization of intellectual functions across various domains. Their presence fosters self-awareness and reflective knowledge, serving as the foundation for cognitive proficiency in the contemporary era. Metacognition skills hold a central position in the development of 21st-century skills, such as problem-solving, critical thinking, creative thinking, reflective thinking, and essential information access capabilities (Damayanti et al., 2022).

These skills encompass comprehensive dimensions of strategic planning (function planning), self-monitoring, and self-evaluation (Akcaoglu, Mor, & Kulekci, 2023). In the educational context, the McKinsey Global Institute report highlights metacognition skills as a primary indicator of students' adaptability to change, especially in preparing for Society 5.0 (Littrell et al., 2024). Findings by Teng and Yue (2023) affirm that metacognition skills are integral components of Higher Order Thinking Skills (HOTS), essential for facilitating students in tackling complex contextual problems.

The importance of metacognition skills in enhancing learning effectiveness has been demonstrated through various studies that correlate them with students' mathematical abilities. These skills are essential for academic success, enabling students to independently manage their cognitive abilities and identify areas for improvement. However, the prevalence of metacognition skills in Indonesia remains low. Many students struggle to understand learning materials and complete tasks requiring high-level thinking skills (Ghofur, Andawiyah, & Mattari, 2023).

Research indicates that the deficit in metacognition skills contributes to low student engagement, leading to monotonous and less dynamic learning processes (Harisuddin, 2021). This is reflected in the National Examination mathematics scores in Bone Regency, which only reached 47.71 (Puspendik, 2019), and the AKM results from the 2022 Public Education Report showing numeracy skills below the minimum competence (Pusmendik, 2022). Observations at SMP Negeri 1 Kahu reveal that students struggle with planning solutions, monitoring processes, and critically evaluating problem-solving, particularly in mathematics.

Several interrelated factors contribute to the lack of metacognition skills among Indonesian students. First, the pedagogical approach in most Indonesian schools remains teacher-centered, limiting opportunities for students to develop independent problem-solving strategies and reflective thinking (Surayanah & Karma, 2023). Many educators still emphasize rote memorization and procedural learning rather than conceptual understanding, which hinders students from actively engaging in metacognitive processes (Hamzah et al, 2023). The rigid curriculum structure, with its strong emphasis on standardized testing, further discourages students from exploring alternative problem-solving strategies and self-reflection (Alguacil et al., 2024).

Second, the limited integration of technology-based learning tools and innovative instructional methods further restricts students' exposure to interactive, inquiry-based learning experiences that foster metacognitive development (Alali et al, 2023). While digital literacy is increasingly promoted, many schools particularly in rural areas lack access to adequate digital infrastructure, limiting the potential for technology-enhanced learning (Khan & Ahmad, 2024). Teachers' unfamiliarity with digital pedagogies also contributes to the underutilization of technology as a means to develop higher-

order thinking skills (Juhari & Zakaria, 2024).

Third, socioeconomic disparities and unequal access to quality education exacerbate the issue (Pusmendik, 2022). Schools in underprivileged regions often lack well-trained educators, sufficient learning resources, and funding for innovative educational programs, making it challenging to implement student-centered and higher-order thinking skill (HOTS) oriented teaching strategies (Faradella, Wiyaka & Egar, 2024). Additionally, disparities in educational quality between urban and rural schools create a significant gap in students' ability to engage in metacognitive learning practices (Verma & Gupta, 2024).

Fourth, cultural factors and traditional educational values influence students' learning attitudes and metacognitive engagement. In many Indonesian communities, education is still perceived as a hierarchical process where students are expected to passively receive knowledge rather than actively construct their understanding (Saripudin et al, 2022). The emphasis on respect for authority in classrooms may discourage students from questioning concepts, reflecting on their learning, or adopting self-regulated learning strategies (Zhang et al., 2024). This cultural dynamic can limit the development of metacognitive skills, as students are less encouraged to take ownership of their learning process.

Given these challenges, integrating innovative learning models, such as Augmented Reality (AR) based educational media, could provide an effective solution to enhance metacognitive skills by promoting active learning, engagement, and self-regulation in problem-solving. AR technology can offer an immersive learning experience that supports students in visualizing abstract concepts, experimenting with different problem-solving strategies, and receiving instant feedback, all of which are essential for fostering metacognitive development (Yadav, 2024). One potential approach is the integration of the traditional Bugis game, Mabbelle, with Augmented Reality (AR) technology. AR offers an immersive learning experience by combining virtual and physical elements, which can enhance students' motivation and interest in understanding abstract concepts (Tan et al, 2022).

In the context of advanced education and learning, the integration of immersive technologies is increasingly recognized as an effective strategy for developing higher-order thinking skills, self-regulated learning, and adaptive competencies required in the twenty-first century. Mathematics education is expected not only to facilitate conceptual understanding but also to provide challenging learning experiences that encourage students to engage in inquiry, reflection, and problem-solving (Verma et al., 2024). Therefore, innovative learning designs that combine local cultural contexts with emerging technologies are essential for creating meaningful and progressive learning environments. The integration of Local Genius Mabbelle and Augmented Reality represents an effort to strengthen educational literacy, technological literacy, and cultural literacy simultaneously, thereby supporting the transformation toward more advanced and sustainable educational practices.

This study aims to develop an educational learning media supported by AR that is valid, practical, and effective, exploring the potential of the Mabbelle game to strengthen students' metacognition skills. By combining AR technology and local wisdom, this research is expected to not only improve students' cognitive skills but also contribute to the preservation of local culture through educational innovation.

2. Method

The research stages were conducted based on the Research and Development (R&D) model, following the ADDIE framework, which includes Analysis, Design, Development, Implementation, and Evaluation.

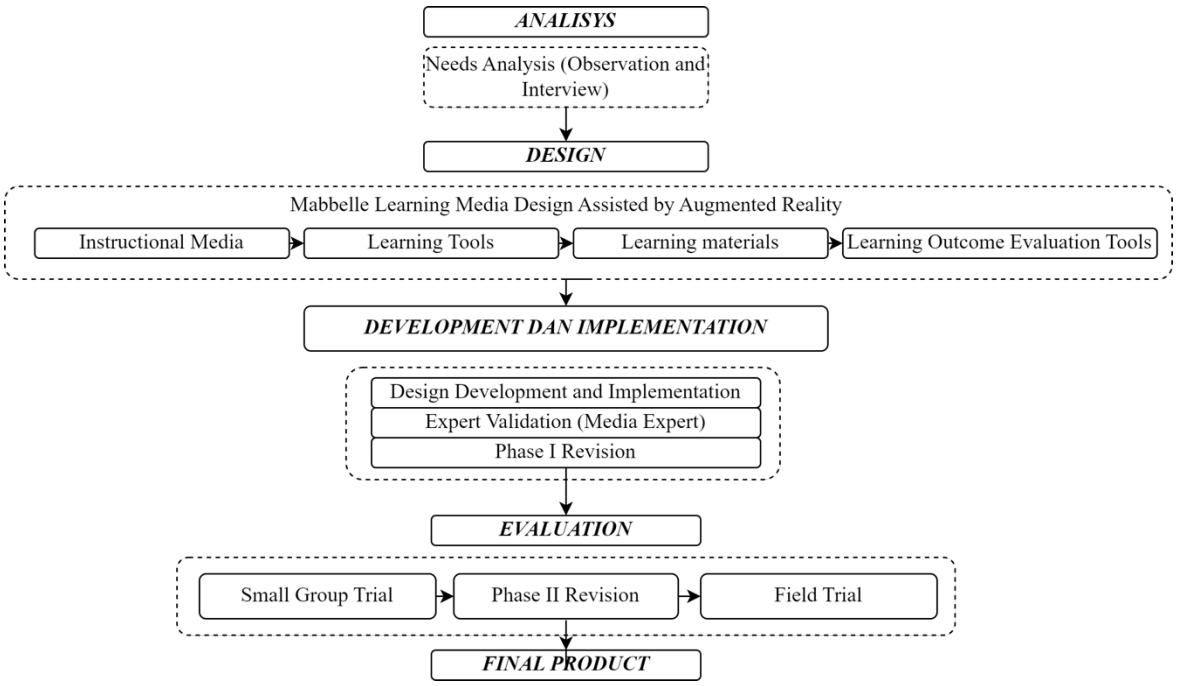

Figure 1. Research Stages

a. Analysis

In the analysis stage, the researcher identifies the needs of the students to determine an appropriate product. This process involves a combination of qualitative and quantitative approaches to ensure a comprehensive understanding of students' learning difficulties and requirements. Data collection methods include classroom observations, teacher interviews, student Focus Group Discussions (FGDs), and diagnostic tests. Classroom observations focus on identifying students' engagement levels, challenges in understanding mathematical concepts, and difficulties in applying metacognitive strategies. Interviews with mathematics teachers explore their perspectives on students' cognitive and metacognitive skill development, the challenges they face in teaching abstract mathematical concepts, and the effectiveness of existing instructional methods.

FGDs with students aim to gather insights into their learning experiences, difficulties in problem-solving, and perceptions of innovative learning media. Additionally, diagnostic tests assess students' initial metacognition skills, problem-solving abilities, and understanding of mathematical concepts related to the curriculum. This analysis is conducted in class VII at SMP Negeri 1 Kahu to uncover the supporting and inhibiting factors for the implementation of the learning media. Furthermore, curriculum analysis is performed to align the media with the basic competencies required in mathematics education.

b. Design

In the design stage, the researcher formulates the learning objectives and prepares the relevant content. The learning objectives are determined based on the findings from

the analysis phase, ensuring that the developed media directly addresses students' needs and enhances their metacognitive skills. Based on these objectives, appropriate learning media are selected, considering relevant learning resources and the suitable environment, including the exploration of Local Genius Mabbelle in mathematics learning. The design process includes the development of instructional materials, interactive learning scenarios, and AR-based visualizations that integrate mathematical concepts with Mabbelle's traditional gameplay. The outcome of this stage is the initial design of the learning media in the form of an educational tool based on Local Genius Mabbelle with Augmented Reality (AR) assistance. To ensure alignment with pedagogical best practices, expert validation is sought from subject matter experts, media designers, and experienced mathematics teachers before progressing to the development phase.

c. Development

In the development stage, the researcher begins to develop the learning media according to the students' needs and the learning objectives. This includes drafting the media, conducting limited trials, expanding trials, and finalizing the media. The initial draft is created based on theories from literature reviews, the characteristics of the media being developed, mathematics learning, and the students' conditions. The draft is then reviewed through discussions with teachers and experts (expert judgment) and tested in a limited setting in class VII E. Evaluation and reflection are conducted during the trial to identify progress and obstacles, which form the basis for the first revision. After revision, a broader trial is conducted in another class (VII D), followed by evaluation and the second revision to obtain the operational model. This model serves as a reference in the media implementation stage through an experimental research approach.

d. Implementation

The implementation stage is the phase of applying the developed learning media to assess its effectiveness. This effectiveness is observed by comparing two classes: the control class (VII A) and the experimental class (VII C). The research method employed is quantitative, using a quasi-experimental design with a non-equivalent control group design.

e. Evaluation

The evaluation stage involves analyzing the practicality of the developed media based on three indicators for improving metacognition skills: planning, self-monitoring, and self-evaluation. Additionally, a preference test on the students is conducted using four indicators: management, engagement, knowledge, and effectiveness to understand students' responses to the Mabbelle-AR media. This evaluation supports the assessment of the media's effectiveness in enhancing students' metacognition skills.

The research duration is four months (May–August 2024), with primary data collection from April 22 to August 18, 2024. The research will be conducted at UPT SMP Negeri 1 Kahu, Palattae Village, Kahu Subdistrict, Bone Regency, South Sulawesi Province. The data collection involves two types of data: primary and secondary data. Primary data is collected through observations, interviews, tests, and questionnaires with students in class VII and the mathematics teachers at SMP Negeri 1 Kahu. Secondary data is collected from literature searches using platforms such as Google Trends, Open Knowledge Maps, Publish or Perish, and analyzed bibliometrically using VOSviewer. The

data collection technique involves five main stages: Analysis, Design, Development, Implementation, and Evaluation. The research subjects include mathematics teachers and class VII students, selected using purposive sampling, leading to the identification of the limited trial class (VII E), extended trial class (VII D), experimental class (VII C), and control class (VII A).

The data analysis aims to assess the validity, practicality, and effectiveness of the developed product (Mabbelle-AR educational learning media). Data obtained from experts and practitioners is analyzed to answer the question of whether the developed learning media is valid, based on its theoretical foundation and internal consistency among the components. The data from field trials are used to answer the categories of practicality and effectiveness of the developed learning.

3. Result and Discussion

This section presents the results of the development and evaluation of the educational teaching media based on Local Genius Mabbelle integrated with Augmented Reality (AR). The discussion encompasses the systematic development process as well as the empirical findings related to the validity, practicality, and effectiveness of the developed media in enhancing students' metacognitive skills.

a. Development of Educational Teaching Media

The Mabbelle-AR educational learning media was developed as a technology-enhanced instructional tool integrating Augmented Reality (AR) with Local Genius Mabbelle to improve students' metacognitive skills, engagement, and problem-solving abilities. The development process followed the ADDIE model, ensuring that the media was systematically designed, validated, and tested before implementation.

1) Media Validity Test

The validity test of the developed media was conducted to determine the extent to which the Mabbelle-AR learning media meets the required standards in terms of content accuracy, instructional design, and technical quality. This validation involved experts from three domains, namely material experts, design experts, and media experts, to ensure the overall feasibility and quality of the product prior to implementation.

Table 1. Media Validity Test Results

	Assessment Aspects	Expert Score		Average Score	Category
		1	2		
Materials Expert	Curriculum	4,00	3,50	3,75	Highly Valid
	Material	3,85	3,00	3,42	Highly Valid
	Grammar	4,00	4,00	4,00	Highly Valid
	Average Total			**3,72**	**Highly Valid**
Design Expert	Display Design	3,60	3,80	3,70	Highly Valid
	Images	4,00	4,00	4,00	Highly Valid
	Average Total			**3,85**	**Highly Valid**
Media Expert	Display Quality	3,00	3,75	3,37	Highly Valid
	Media Engineering	4,00	3,50	3,37	Highly Valid
	Implementation	4,00	4,00	4,00	Highly Valid
	Average Total			**3,58**	**Highly Valid**

The results from expert validation indicate that the Mabbelle-AR learning media is highly valid, with an average score of 3.72 from material experts, 3.85 from design experts, and 3.58 from media experts. These scores suggest that the media meets the required content, design, and technical quality standards. The high validation scores suggest that embedding cultural elements in digital learning media can enhance its pedagogical relevance. Previous research has demonstrated that culturally integrated learning models improve students' cognitive and affective engagement (Li & Lajoie, 2022). Similar results were reported in a study by (Cheung & Ng, 2022), which found that using local games in digital education strengthens contextual learning and increases motivation.

2) Learning Devices Validity Test

In addition to media validation, the supporting learning devices were also evaluated to ensure their alignment with the instructional objectives and the characteristics of AR-based learning. This validation aims to confirm that all instructional components function coherently in facilitating effective learning and supporting the development of students' metacognitive skills.

Table 2. Validity Test of Learning Devices

Assessment Aspect	Expert Score		Average Score	Category
	1	2		
Learning Tools and Objectives	4,00	4,00	4,00	Highly Valid
Experimental Class Teaching Module	4,00	3,57	3,78	Highly Valid
Teaching Materials	3,83	3,83	3,83	Highly Valid
Assessment Sheets	4,00	3,66	3,83	Highly Valid
Question Grids	4,00	3,40	3,70	Highly Valid
Student Worksheets	4,00	4,00	4,00	Highly Valid
Average Total			**3,85**	**Highly Valid**

Supporting learning devices such as Learning Tools and Objectives**,** teaching modules, Teaching Materials, assessment instruments, Question Grids, and student worksheets were also validated by experts. The validation results showed an average score of 3.85 (highly valid), indicating that the instructional materials align well with the curriculum, cognitive learning objectives, and technological affordances of AR-based learning.

A study by Koparan et al., (2023) also found that the effectiveness of AR learning environments depends on well-structured instructional materials, which guide students through complex learning processes. These results reinforce the importance of integrating detailed learning support materials into AR-based education.

3) Practicality Test

Following the validation phase, a practicality test was conducted to assess the usability and implementation feasibility of the developed Mabbelle-AR learning media in real classroom settings. This evaluation focuses on how easily the media can be used by teachers and students, as well as how effectively it supports learning activities. The practicality assessment was based on user responses, covering four key indicators: management, activeness, knowledge, and effectiveness.

Table 3. Percentage of Practical Assessment Results (Teacher)

Practicality Test Indicator	Teacher 1	Teacher 2	Teacher 3
Management	32	32	32
Activeness	24	24	24
Knowledge	28	28	28
Effectiveness	16	16	16
Total Score	**100**	**100**	**100**
Percentage (%)	**100**	**100**	**100**
Criteria	**Very Practical**	**Very Practical**	**Very Practical**

The results of the teacher response analysis show that overall the implementation aspects of the educational learning media Mabbelle-AR have met the criteria of being very practical. This is also supported by the positive responses of students in the trial class

Table 4. Student Practical Results

	Average Practicality Test Score				Total Score	Information
	Management	Aktiveness	Knowledge	Effectiveness		
Limited Trial	27.11	11.78	22.63	14.52		
Percentage (%)	**96.83**	**98.15**	**94.29**	**90.74**	76.04	Practical
Criteria	Very Practical	Very Practical	Very Practical	Very Practical		
Wide Trial	27.30	11.85	23.15	15.15		
Percentage (%)	**97.51**	**98.74**	**96.46**	**94.70**	77.45	Practical
Criteria	Very Practical	Very Practical	Very Practical	Very Practical		
Experimental Test	27.94	11.89	23.89	15.83		
Percentage (%)	**99.80**	**99.07**	**99.54**	**98.96**	79.56	Practical
Criteria	Very Practical	Very Practical	Very Practical	Very Practical		

Based on table 4 above, it can be concluded that the Mabbelle-AR teaching media that was developed can be practically applied to support students' metacognition skills in the mathematics subject of flat shapes.

These findings align with previous studies that highlight AR's potential to enhance student engagement and interaction in mathematics learning (Buentello et al., 2021). However, some researchers argue that the practical benefits of AR-based learning may be limited if students lack prior exposure to digital learning environments (Lo et al., 2021).

4) Effectiveness Test

The effectiveness test was conducted to evaluate the impact of the Mabbelle-AR learning media on students' metacognitive skills. This phase aims to measure the extent to which the developed media contributes to learning improvement, particularly in terms of students' ability to plan, monitor, and evaluate their cognitive processes. The effectiveness was analyzed through a comparison of pretest and posttest results between the experimental and control groups using the N-Gain score.

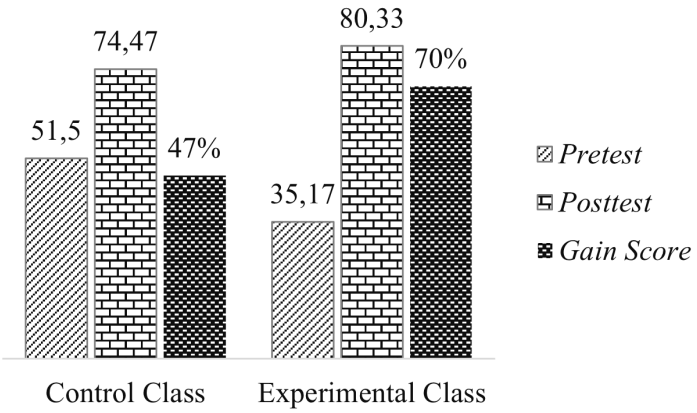

Figure 2. Comparison of N-Gain Score of Control Class and Experimental Class

The figure above shows the percentage of increase in the control class and the experimental class. The increase (gain score) in the control class from the pretest and posttest results obtained a score of 22.97 (low) or an increase of 47% (less effective). Meanwhile, the increase (gain score) in the experimental class obtained a score of 45.16 (high) or 70% in the effective category. This indicates that the implementation of Local Genius Mabbelle integrated education assisted by Augmented Reality is more effective in improving students' metacognition skills compared to the Project Based Learning learning model (control class).

This finding is consistent with studies on AR-enhanced problem-solving, which found that interactive and immersive learning experiences improve students' ability to plan, monitor, and evaluate their cognitive processes (Baxter & Hainey, 2024). However, some studies suggest that AR learning effectiveness is influenced by students' digital literacy and ability to self-regulate their learning (Yuniarti et al., 2024).

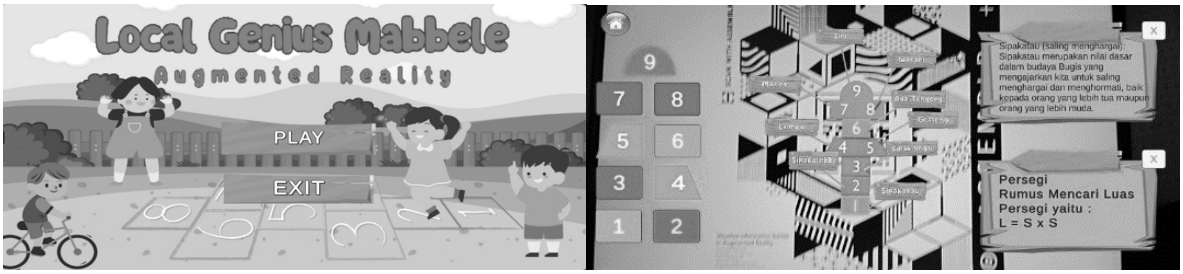

Figure 3. Display of Educational Teaching Media (Mabbelle-AR)

b. Exploring Local Genius Mabbelle with Augmented Reality Assistance

The implementation of local genius Mabbelle media in the learning process contains a philosophy that carries cultural symbols, such as the integration of values presented in each visualization of the form of the Mabbelle game path pattern in order to realize cultural resilience, namely Sipakatau, Sipakalebbi, Sipakainge, Lempu, Getteng, Ada Tongeng, Macca, Warani, and Siri' which are reflected in each stage of learning. The integration of Local Genius Mabbelle into Augmented Reality (AR) learning media presents a unique approach to mathematics education that is deeply rooted in cultural values (Saripudin et al., 2022). Unlike conventional mathematics instruction, which

often lacks contextual and culturally relevant elements, Mabbelle-AR bridges traditional knowledge with modern educational technology. The traditional Mabbelle game, widely recognized among the Bugis community, serves as the foundation for an interactive learning experience where students engage with mathematical concepts through familiar cultural representations (Lo et al., 2021). The stages of implementing Mabbelle-AR media in the learning process are carried out using 4 (four) steps through the adaptation of Bugis cultural values according to the stages of the Mabbelle game, namely: 1) The Sipatudang stage (exploration) is the stage where the teacher explains the form and pattern of the Mabbelle game path by mentioning the flat shapes contained in the path pattern, as well as the introduction of character values in the Mabbelle game; 2) The Sipattuju stage (connection) the teacher connects the form of the Mabbelle game path pattern with flat shapes, and explains the formula used in solving problems; 3) Sipalolongeng stage (problem solving) the teacher directs students to solve flat shape problems in the form of Mabbelle game track patterns using Augmented Reality media; 4) Sipalempu stage (review) is a presentation stage followed by a conclusion of the results of the problem solving process that has been carried out in the previous stage.

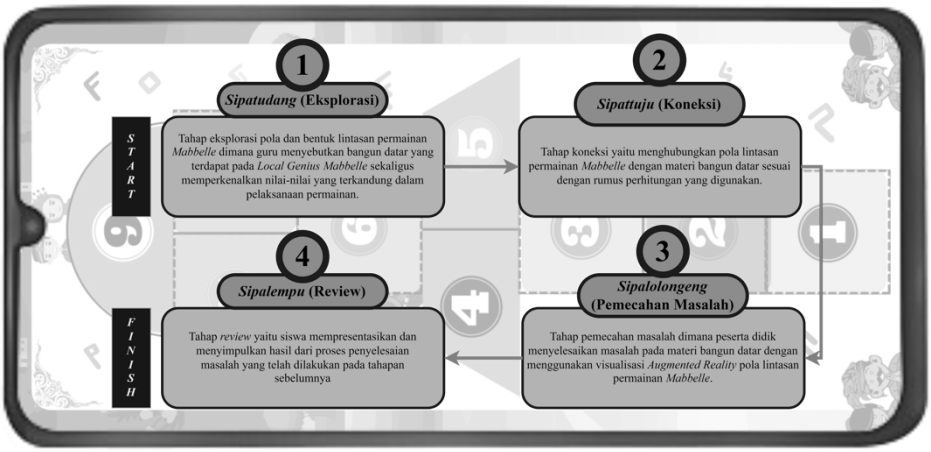

Figure 4. Stages of Implementing Learning Media

Mabbelle-AR exploration produces Instructional Effects in the form of increased metacognition skills and understanding of mathematical concepts, as well as Nurturant Effects in the form of increased motivation, engagement, and strengthening of local cultural values. This impact is in line with the principles of Vygotsky's social constructivism theory, which emphasizes the importance of social interaction and scaffolding in learning (Michalsky, 2024). This media not only enriches students' learning experiences but also builds a strong foundation for collaborative and culturally context-based learning.

However, while this study confirms the effectiveness of cultural-based AR learning, some researchers have noted that contextualized digital education requires careful implementation to ensure accessibility for diverse learners (Mendrofa et al., 2024). Future iterations of Mabbelle-AR should explore adaptive learning features that allow personalization based on students' varying skill levels.

Thus, the implementation of this educational teaching media can support the achie-

vement of Sustainable Development Goals point 4, namely quality education.

Furthermore, the integration of AR technology within culturally responsive learning environments reflects the characteristics of progressive education, where students actively construct knowledge through authentic experiences and contextual problem-solving activities. The Mabbelle-AR model promotes advanced learning by encouraging learners to connect mathematical concepts with real-life cultural contexts while simultaneously developing technological literacy (Mokmin & Apandi, 2025). Such an approach aligns with current educational trends emphasizing learner-centered, technology-enhanced, and future-oriented learning practices.

c. The Influence of Mabbelle-AR Educational Media on Metacognition Skills

The influence of Local Genius Mabbelle learning media assisted by Augmented Reality on metacognition skills can be seen from the results of the questionnaire that shows the responses of teachers and students in the learning process. The learning media that the team developed in this research was adapted from the Mabbelle game trajectory pattern which is full of flat shapes in mathematics learning. Based on this trajectory pattern, the application of Mabbelle-AR learning media in this learning consists of four core stages, namely the Sipatudang (exploration), Sipattuju (connection), Sipalolongeng (problem solving) and Sipalempu (review) stages.

Figure 5. Media Implementation Process

Through a series of stages in the application of this teaching media, students are slowly able to hone their planning skills (planning the problem-solving process), monitoring (monitoring the steps in solving the problem), and assessment (evaluating the implementation of problem solving) formed when the teacher gives various questions through the Mabbelle-AR teaching media (Tan et al., 2022). The system for giving various questions in this application is presented in the form of a door prize box containing numbers. Each number contains 5 fill-in questions as a form of quiz for students that can be selected to be worked on. By providing various questions, students can more easily understand a series of questions, especially in this research using flat shape material. The application of this teaching media is very helpful in the activeness of students in identifying the shape of the Mabbelle game path pattern in the form of Augmented Reality media. Based on a series of learning stages provided, it can be concluded that the application of the Local Genius Mabbelle teaching media assisted by Augmented Reality has a significant positive influence on improving students' metacognition skills.

The findings show a significant improvement in students' motivation, engagement, and problem-solving skills. Student responses to management, activity, knowledge, and effectiveness indicators ranged from 81.25% to 100%, indicating a highly positive reception of the learning me-

dia. Increased student motivation and interest in learning also correlated with improvements in metacognitive awareness **(**Yunus et al., 2025**)**.

This aligns with previous studies that found AR-based learning environments enhance students' cognitive engagement by making abstract mathematical concepts more tangible. Similarly, research by (Sangwan et al., 2022) demonstrated that interactive learning models incorporating cultural elements foster deeper conceptual understanding and problem-solving skills. However, other studies suggest that the effectiveness of AR-assisted learning varies depending on students' prior knowledge and self-regulation abilities (Dewi et al., 2024).

Several studies have examined the impact of AR technology on metacognitive skill development. Research by (Suhail, Bahroun & Ahmed, 2024) found that AR-enhanced instructional media improved students' ability to plan and monitor learning outcomes by providing real-time feedback and immersive problem-solving experiences. This is consistent with the results of this study, where students using Mabbelle-AR demonstrated enhanced self-regulation and cognitive awareness.

However, not all AR-based learning interventions yield uniform results. Studies by (Mokmin et al., 2025) indicate that while AR-based learning can increase engagement, its long-term effects on metacognitive retention depend on the level of instructional scaffolding provided by educators. This is particularly relevant to this study, as the effectiveness of Mabbelle-AR may be influenced by teachers' ability to facilitate student interaction with the media effectively.

Additionally, the integration of local cultural elements in AR-based learning has been less explored in previous research. While studies by (Brown *et al.,* 2021) emphasize the cognitive benefits of AR in STEM education, fewer studies have examined how culturally contextualized digital learning media impact student engagement and learning outcomes. The Mabbelle-AR model fills this gap by demonstrating that incorporating traditional Bugis game elements into AR-based mathematics learning fosters both metacognitive growth and cultural preservation.

d. Strengthening Collaborative Learning through Mabbelle-AR Implementation

One of the significant findings of this study is the important role of Mabbelle-AR learning media in strengthening collaborative learning among students. The integration of Augmented Reality (AR) technology with Local Genius Mabbelle creates an interactive and immersive learning environment that encourages students to actively engage in peer discussions, cooperative problem-solving, and shared decision-making processes during learning activities (Susanto & Nurtamam, 2024). Unlike conventional mathematics instruction, where learning is often individualistic and procedural, the Mabbelle-AR approach promotes social interaction as a fundamental aspect of knowledge construction.

To provide empirical support for this finding, observational data on students' collaborative learning activities were quantified and compared between the control and experimental classes. The results are presented in Table 5.

Table 5. Students' Collaborative Learning Activity in Control and Experimental Class

Collaborative Indicators	Control Class (%)	Experimental Class (%)
Peer Discussion	65.20	89.75
Cooperative Problem Solving	61.45	91.30
Knowledge Sharing	63.10	88.90
Participation in Group Tasks	66.80	93.15
Decision-Making Involvement	59.75	87.40
Average	**63.26**	**90.10**

As shown in Table 5, the experimental class demonstrated a substantially higher level of collaborative engagement compared to the control class. The average score of collaborative activities in the experimental class reached 90.10%, significantly exceeding the control class, which only achieved 63.26%. The highest improvement was observed in participation in group tasks (93.15%) and cooperative problem solving (91.30%), indicating that students were more actively involved in teamwork and collective knowledge construction when using Mabbelle-AR media. These findings are consistent with previous studies indicating that AR-based collaborative learning environments enhance knowledge sharing, communication skills, and critical thinking (Kumar et al., 2022).

In addition to observational data, students' perceptions of collaborative learning were also measured through questionnaires to capture their subjective experiences during the learning process. The results are presented in Table 6.

Table 6. Students' Perception of Collaborative Learning Using Mabbelle-AR

Indicators	Average Score (Scale 1–4)	Category
Interaction Quality	3.78	Very Good
Communication Effectiveness	3.72	Very Good
Group Engagement	3.85	Very Good
Shared Problem Solving	3.80	Very Good
Responsibility in Group Work	3.76	Very Good
Average Total	**3.78**	**Very Good**

Based on Table 6, students' perceptions of collaborative learning are consistently categorized as "very good," with an overall average score of 3.78. The highest score was observed in group engagement (3.85), suggesting that students felt highly involved and motivated during collaborative activities. This indicates that the Mabbelle-AR learning media not only enhances observable collaborative behaviors but also positively influences students' attitudes toward teamwork and shared learning experiences.

The effectiveness of collaborative learning in this study is closely related to the structured learning stages embedded in the Mabbelle-AR model, namely Sipatudang (exploration), Sipattuju (connection), Sipalolongeng (problem solving), and Sipalempu (review). These stages provide a scaffolded learning process that

systematically facilitates interaction, discussion, and collective reasoning among students. Particularly in the Sipalolongeng stage, students are required to work collaboratively to analyze AR-generated geometric patterns and determine appropriate problem-solving strategies, thereby strengthening peer interaction and shared cognitive engagement (Cetintav & Yilmas, 2023).

These findings align with Vygotsky's social constructivism theory, which emphasizes the importance of social interaction and scaffolding in learning processes (Michalsky, 2024). The use of AR technology further enhances this interaction by providing immersive visualizations that support shared understanding and collaborative meaning-making. However, some studies suggest that successful implementation of AR for teamwork requires structured role assignments to prevent unequal participation and ensure balanced engagement among students (Xu & Correia, 2024).

Despite its advantages, several challenges were identified during implementation. Some students experienced difficulties in coordinating group decisions and managing differing problem-solving approaches. This finding is consistent with previous research suggesting that collaborative learning is most effective when supported by structured facilitation and guided reflection (Er et al., 2021). Therefore, future implementations of Mabbelle-AR should incorporate more explicit collaborative scaffolding strategies, such as role distribution and guided peer interaction.

Overall, the results indicate that the Mabbelle-AR learning media not only improves students' metacognitive skills but also plays a crucial role in strengthening collaborative learning as a key competency in 21st-century education. The integration of cultural elements and advanced technology provides a holistic learning experience that supports both cognitive and social development, making it a promising model for innovative and context-based mathematics learning.

Beyond its contribution to collaborative learning, further analysis is necessary to examine how the Mabbelle-AR learning media influences students' metacognitive development and broader educational outcomes. Therefore, additional investigations were conducted to explore students' metacognitive components, learning motivation, cultural value internalization, and the educational implications of implementing Mabbelle-AR in mathematics learning.

e. Impact of Mabbelle-AR on Students' Metacognitive Development

The development of metacognitive skills is one of the primary objectives of contemporary mathematics education because these skills enable students to become independent learners who are capable of planning, monitoring, and evaluating their own learning processes. Within the framework of advanced education and learning, metacognition is considered a critical competency that supports lifelong learning, adaptive thinking, and complex problem-solving (Zhang et al., 2024). Therefore, learning environments should be intentionally designed to provide challenging learning experiences that encourage students to reflect upon their cognitive strategies and make informed decisions throughout the learning process. In this study, the implementation of Mabbelle-AR learning media demonstrated a significant contribution to the enhancement of students' metacognitive development. The integration of Local Genius Mabbelle with Augmented Reality technology creates a learning

environment that not only facilitates conceptual understanding but also encourages students to actively regulate their cognitive activities throughout the learning process (Faradella et al., 2024).

The structured learning stages embedded within the Mabbelle-AR model, namely Sipatudang (exploration), Sipattuju (connection), Sipalolongeng (problem solving), and Sipalempu (review), provide systematic opportunities for students to engage in metacognitive practices. During the Sipatudang stage, students identify mathematical concepts represented through Mabbelle game patterns, allowing them to activate prior knowledge and establish learning goals. In the Sipattuju stage, students connect the identified concepts with mathematical formulas and procedures, thereby strengthening their planning abilities. Furthermore, the Sipalolongeng stage requires students to solve contextual problems using AR visualizations, which encourages continuous monitoring of their problem-solving strategies (Rifanka et al., 2025). Finally, the Sipalempu stage facilitates reflection and evaluation of learning outcomes, enabling students to assess the effectiveness of the strategies they have employed.

To further examine the influence of Mabbelle-AR on students' metacognitive development, an analysis was conducted based on the core dimensions of metacognition. The results are presented in Table 7.

Table 7. Improvement of Metacognitive Skill Components

Metacognitive Components	Pretest (%)	Posttest (%)	Gain (%)	Category
Planning	48.50	80.25	65.46	High
Monitoring	44.75	78.90	61.85	High
Evaluation	42.60	77.15	60.92	High
Self-Regulation	46.30	79.85	62.48	High
Average	**45.54**	**79.04**	**62.68**	**High**

Table 7 demonstrates that all metacognitive components experienced substantial improvement after the implementation of Mabbelle-AR learning media. The highest gain was observed in the planning component (65.46%), indicating that students became more capable of identifying learning objectives, selecting appropriate problem-solving strategies, and organizing the steps necessary to solve mathematical problems. This finding suggests that the exploration and connection stages of Mabbelle-AR effectively support students in preparing cognitive strategies before engaging in complex tasks. The monitoring component also showed a significant increase (61.85%), reflecting students' improved ability to observe and control their thinking processes while solving mathematical problems. Similarly, the evaluation component achieved a gain score of 60.92%, indicating that students became more reflective in assessing the effectiveness of their solutions and identifying possible errors. The improvement in self-regulation (62.48%) further confirms that students developed stronger autonomy and responsibility in managing their learning activities. These findings support previous studies that emphasize the role of immersive and interactive learning environments in promoting self-regulated learning and metacognitive awareness (Suhail et al., 2024). The results also indicate that the

combination of culturally relevant learning contexts and AR technology provides meaningful opportunities for students to engage in higher-order thinking processes, thereby facilitating deeper metacognitive development.

In addition to enhancing metacognitive skills, the implementation of Mabbelle-AR also positively influenced students' learning motivation and engagement during mathematics instruction. Motivation is widely recognized as an important factor that determines students' willingness to participate actively in learning activities and persist when facing challenging tasks. The interactive nature of AR technology, combined with culturally familiar elements derived from the Mabbelle game, appears to increase students' enthusiasm and interest in learning mathematics (Cetintav & Yilmaz, 2023). The results of students' perceptions regarding learning motivation and engagement are presented in Table 8.

Table 8. Students' Learning Motivation and Engagement toward Mabbelle-AR

Indicators	Mean Score	Percentage (%)	Category
Learning Motivation	3.82	95.50	Very Good
Learning Interest	3.87	96.75	Very Good
Learning Engagement	3.91	97.75	Very Good
Learning Confidence	3.78	94.50	Very Good
Average	**3.85**	**96.13**	**Very Good**

The findings presented in Table 8 reveal that students demonstrated highly positive perceptions toward the implementation of Mabbelle-AR learning media. Among the measured indicators, learning engagement achieved the highest score (97.75%), indicating that students were actively involved in classroom discussions, collaborative problem-solving activities, and interactions with AR-based learning content.

This result suggests that the immersive characteristics of AR technology successfully attracted students' attention and encouraged sustained participation throughout the learning process. According to Yadav (2024) Learning interest also recorded a high percentage (96.75%), demonstrating that students perceived mathematics learning as more enjoyable and meaningful when integrated with local cultural elements. Meanwhile, the learning motivation indicator reached 95.50%, indicating that students were encouraged to invest greater effort in completing learning tasks and overcoming difficulties encountered during problem-solving activities.

Learning confidence also showed a very positive result (94.50%), suggesting that students became more confident in expressing ideas, solving mathematical problems, and participating in classroom interactions. These findings are consistent with previous research indicating that AR-based learning environments enhance students' motivation, engagement, and academic confidence by providing interactive and contextualized learning experiences (Baxter & Hainey, 2024). Furthermore, the integration of local wisdom within digital learning media contributes to students' sense of familiarity and cultural identity, thereby strengthening their emotional connection to the learning process.

Overall, the findings indicate that Mabbelle-AR not only improves students' metacognitive skills but also fosters higher levels of motivation and engagement,

creating a comprehensive learning environment that supports both cognitive and affective development. These outcomes reinforce the potential of culturally integrated AR learning media as an innovative approach to promoting meaningful, reflective, and student-centered mathematics learning.

f. Educational and Cultural Implications of Mabbelle-AR Implementation

The implementation of Mabbelle-AR learning media provides broader implications beyond the improvement of students' metacognitive skills and collaborative learning. The integration of Augmented Reality (AR) technology with Local Genius Mabbelle represents an innovative educational approach that combines technological advancement, cultural preservation, and student-centered pedagogy (Teng & Yue, 2023). In the context of 21st-century education, learning innovations are expected not only to improve academic achievement but also to foster cultural awareness, digital literacy, and character development (Pahrizal et al., 2025). Therefore, the implementation of Mabbelle-AR offers significant educational and cultural contributions that can support sustainable educational development.

One of the distinctive features of Mabbelle-AR is its ability to transform local cultural values into meaningful learning experiences. The traditional Mabbelle game contains various Bugis cultural values such as Sipakatau (mutual respect), Sipakalebbi (mutual appreciation), Sipakainge (mutual reminding), Lempu (honesty), Getteng (consistency), Ada Tongeng (truthfulness), Macca (intelligence), Warani (courage), and Siri' (self-respect). Through AR-supported learning activities, these values are not merely introduced theoretically but are embedded within students' learning interactions and problem-solving processes (Priandani et al., 2025). As a result, students are able to simultaneously develop academic competencies and cultural awareness.

To examine the extent to which students perceived the integration of cultural values within the Mabbelle-AR learning process, a perception analysis was conducted. The results are presented in Table 9.

Table 9. Students' Perception of Bugis Cultural Values Embedded in Mabbelle-AR

Cultural Values	Mean Score	Percentage (%)	Category
Sipakatau (Mutual Respect)	3.86	96.50	Very Good
Sipakalebbi (Mutual Appreciation)	3.82	95.50	Very Good
Sipakainge (Mutual Reminder)	3.79	94.75	Very Good
Lempu (Honesty)	3.88	97.00	Very Good
Getteng (Consistency)	3.80	95.00	Very Good
Macca (Wisdom and Intelligence)	3.91	97.75	Very Good
Warani (Courage)	3.77	94.25	Very Good
Siri' (Self-Respect)	3.85	96.25	Very Good
Average	**3.84**	**95.88**	**Very Good**

The findings in Table 9 indicate that students positively perceived the integration of Bugis cultural values within the learning process. The highest score was achieved by Macca (97.75%), suggesting that students viewed the learning activities as opportunities to develop intelligence, critical thinking, and problem-solving abilities. High

scores were also obtained for Lempu (97.00%) and Sipakatau (96.50%), demonstrating that students recognized the importance of honesty and mutual respect during collaborative learning activities. These findings indicate that Mabbelle-AR serves not only as a learning medium but also as a vehicle for character education.

The incorporation of cultural values provides meaningful contexts that help students understand how mathematical learning can be connected to social and cultural realities. Furthermore, the positive perception of cultural values suggests that technology-based learning does not necessarily diminish cultural identity (Mendrofa et al., 2024). Instead, when appropriately designed, digital learning innovations can strengthen cultural preservation by introducing traditional values in ways that are relevant to contemporary learners (Yumna et al., 2024). This finding contributes to the growing body of literature on culturally responsive pedagogy, which emphasizes the importance of integrating local culture into educational practices to enhance both academic and socio-cultural outcomes.

Beyond cultural preservation, the implementation of Mabbelle-AR also contributes significantly to the development of essential educational competencies required in modern learning environments. The learning design developed in this study reflects an innovative learning design framework that integrates cultural resources, immersive technologies, collaborative learning activities, and metacognitive scaffolding into a unified instructional model. Such integration is essential for preparing students to navigate increasingly complex educational challenges in the digital era (Nugraha et al., 2024). These competencies include digital literacy, critical thinking, collaboration, communication, and problem-solving abilities. To identify the educational contributions of Mabbelle-AR, students' perceptions regarding educational benefits were analyzed and are presented in Table 10.

Table 10. Educational Benefits of Mabbelle-AR Learning Media

Educational Aspects	Mean Score	Percentage (%)	Category
Digital Literacy	3.84	96.00	Very Good
Critical Thinking	3.88	97.00	Very Good
Problem Solving Skills	3.91	97.75	Very Good
Communication Skills	3.80	95.00	Very Good
Collaboration Skills	3.89	97.25	Very Good
Learning Independence	3.76	94.00	Very Good
Average	**3.85**	**96.17**	**Very Good**

Table 10 demonstrates that Mabbelle-AR positively supports multiple dimensions of educational development. The highest percentage was found in problem-solving skills (97.75%), indicating that students perceived the learning activities as highly effective in helping them solve mathematical problems through exploration and analysis. Collaboration skills also received a high score (97.25%), which aligns with the previous findings regarding collaborative learning. Furthermore, digital literacy achieved a score of 96.00%, suggesting that students became more familiar with technology-enhanced learning environments.

The positive results across all educational aspects indicate that Mabbelle-AR facilitates holistic learning experiences that integrate cognitive, technological, and social competencies. These findings support contemporary educational frameworks emphasizing the development of 21st-century skills. The use of AR technology provides students with opportunities to interact with digital content in meaningful ways, while the collaborative nature of Mabbelle-based activities encourages communication and teamwork (Almubarak et al., 2025). Consequently, Mabbelle-AR can be considered an effective educational innovation that addresses both current educational needs and future workforce competencies.

In addition to educational benefits and cultural preservation, the implementation of Mabbelle-AR contributes to broader educational goals, particularly the achievement of Sustainable Development Goal (SDG) 4 concerning quality education. To identify the broader implications of the developed learning media, an educational impact analysis was conducted and is presented in Table 11.

Table 11. Broader Educational Implications of Mabbelle-AR Implementation

Educational Dimension	Key Findings	Benefits	Long-Term Implications
Metacognitive Development	Improved planning, monitoring, and evaluation skills	Enhanced self-regulated learning	Lifelong learning readiness
Collaborative Learning	Increased teamwork and peer interaction	Stronger social competence	Better communication and cooperation skills
Cultural Preservation	Strengthened understanding of Bugis values	Increased cultural awareness	Sustainable cultural transmission
Technology Integration	Effective use of AR in mathematics learning	Improved digital literacy	Readiness for digital transformation
Student Engagement	High motivation and active participation	Better learning experience	Increased academic persistence
Educational Innovation	Integration of local wisdom and AR technology	Contextualized learning environment	Replicable learning model for other regions

Table 11 summarizes the broader educational implications of implementing Mabbelle-AR within mathematics education. The findings suggest that the benefits of the developed learning media extend beyond short-term learning outcomes. In terms of metacognitive development, students demonstrated stronger abilities to regulate and evaluate their own learning processes, which are essential characteristics of lifelong learners (Rifanka et al., 2025). Collaborative learning outcomes indicate that students developed social competencies that are increasingly important in modern educational and professionais settings. Furthermore, cultural preservation emerged as a significant contribution, highlighting the potential of technology-enhanced learning media to sustain local cultural heritage in the digital era. The integration of AR technology also supports educational digitalization by providing students with authentic experiences in utilizing emerging technologies for learning purposes. Importantly, the educational innovation embodied in Mabbelle-AR demonstrates how local wisdom and advanced technology can coexist to create meaningful and contextualized learning experiences (Yumna et al., 2024). This model may serve as a reference for educators and researchers seeking to develop culturally responsive educational

technologies in different regions and contexts.

Overall, the implementation of Mabbelle-AR provides substantial educational and cultural benefits by fostering metacognitive growth, strengthening cultural identity, enhancing 21st-century competencies, and supporting the realization of quality education. The findings suggest that combining local wisdom with emerging technologies represents a promising strategy for developing innovative, inclusive, and sustainable learning environments that are responsive to both global educational demands and local cultural contexts.

4. Conclusion

The development of educational learning media based on Local Genius Mabbelle assisted by Augmented Reality in this research shows valid, practical and effective results. The validity of this educational media is comprehensively validated by material experts, design experts and media experts. Based on the validation results of the three aspects, the educational learning media developed obtained an average score that is included in the very valid category, which indicates that this media has met high quality standards in terms of content, design, and technical aspects. Then, in supporting the implementation of learning, validation was also carried out on the learning devices used including learning tools and objectives, teaching modules, teaching materials, assessment sheets, question grids and Student Worksheets which showed scores that were in the very valid category.

This indicates that all supporting components of learning have been designed and arranged optimally to support an effective learning process. Furthermore, the practicality of the media shows very practical results to be implemented in the learning process, this can be seen from the results of student responses with an average of 3.85, while from teachers it is 3.95. The focus of this research is on strengthening students' metacognition skills from the implementation of educational learning media based on Local Genius Mabelle assisted by Augmented Reality which shows a significant increase as evidenced by the results of pre-test and post-test testing where in the control class with a score of 22.97 or 47% in the less effective category, then in the experimental class with a score of 45.16 or 70% in the effective category. Therefore, it can be concluded that the educational learning media developed is not only valid and practical, but also effective in improving students' metacognition skills.

The implementation of this media also produces instructional and nurturant effects that support mathematics learning while fostering metacognitive awareness, collaborative competence, technological literacy, and cultural appreciation. The integration of Local Genius Mabbelle and Augmented Reality offers an innovative and progressive learning design that contributes to advanced education and learning, supports challenging and meaningful learning experiences, and promotes the development of educational, scientific, and technological literacy. Therefore, Mabbelle-AR has strong potential to serve as a sustainable instructional model for future-oriented mathematics education.

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