JURNAL ABSIS
Jurnal Pendidikan Matematika dan Matematika
Vol. 8 No. 2, August 2025

ENHANCING MATHEMATICAL COMPETENCE THROUGH AUGMENTED REALITY: AN EXPLORATORY STUDY USING BEST AR IN GEOMETRY LEARNING

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ABSTRACT The integration of digital technology in mathematics education holds immense potential to transform abstract concepts into concrete experiences. This study explores the impact of an Augmented Reality (AR)-based learning application, *Best AR*, on enhancing the mathematical competence of fifth-grade students in Malaysia. Conducted in a tutoring center using an exploratory qualitative approach, the research investigates how the interactive features of *Best AR*—including 3D object simulations, mini-games, and quizzes—support conceptual understanding, engagement, and problem-solving skills, particularly in learning three-dimensional geometry. Data were collected through interviews, observations, and documentation, and analyzed thematically. The findings reveal that *Best AR* improved students' ability to visualize and manipulate geometric objects, fostered collaboration, increased motivation, and enhanced logical reasoning. The application's mobile accessibility and adaptive feedback promoted self-regulated learning, while its gamified elements made mathematics more engaging and enjoyable. Despite challenges in device access and teacher preparedness, the study underscores the potential of AR to bridge gaps in technology integration and enrich mathematics instruction. Implications for curriculum alignment, teacher training, and scalable adoption of AR media in informal learning contexts are discussed.

Keywords: augmented reality, mathematical competence, geometry learning, gamification, educational technology

ABSTRAK Integrasi teknologi digital dalam pendidikan matematika memiliki potensi besar untuk mentransformasi konsep-konsep abstrak menjadi pengalaman belajar yang konkret. Penelitian ini bertujuan untuk mengeksplorasi pengaruh media pembelajaran berbasis Augmented Reality (AR) bernama *Best AR* terhadap peningkatan kompetensi matematis siswa kelas V di Malaysia. Studi ini dilaksanakan di sebuah pusat bimbingan belajar dengan pendekatan kualitatif eksploratif, untuk menelusuri bagaimana fitur interaktif *Best AR*—seperti simulasi objek 3D, mini-games, dan kuis—mendukung pemahaman konsep, keterlibatan, dan keterampilan pemecahan masalah, khususnya dalam pembelajaran geometri bangun ruang. Data dikumpulkan melalui wawancara, observasi, dan dokumentasi hasil belajar, kemudian dianalisis secara tematik. Temuan menunjukkan bahwa *Best AR*

https://doi.org/10.30606/absis.v8i2.3253

meningkatkan kemampuan siswa dalam memvisualisasikan dan memanipulasi objek geometri, mendorong kolaborasi, meningkatkan motivasi, serta memperkuat penalaran logis. Aksesibilitas aplikasi melalui perangkat seluler dan fitur umpan balik adaptif mendukung pembelajaran mandiri, sementara elemen gamifikasi membuat pembelajaran matematika lebih menarik dan menyenangkan. Meskipun terdapat tantangan seperti keterbatasan perangkat dan kesiapan guru, studi ini menegaskan potensi AR dalam menjembatani kesenjangan integrasi teknologi dan memperkaya pembelajaran matematika. Implikasi bagi keselarasan kurikulum, pelatihan guru, dan adopsi media AR secara luas dalam konteks pembelajaran informal turut dibahas.

Kata-kata kunci: augmented reality, kompetensi matematis, pembelajaran geometri, gamifikasi, teknologi pendidikan

INTRODUCTION

The integration of technology in mathematics education has become increasingly important in the digital era. It enhances the flexibility and accessibility of learning, allowing students to study at their own pace, anytime and anywhere (Elfrianto & Tanjung, 2022; Hidayat & Firmanti, 2024). Moreover, the advancement of digital technologies requires students to continuously adapt to new tools and environments, placing demands on education systems to evolve accordingly (Rosnelli et al., 2024; Tanjung et al., 2023).

Internationally, various countries have demonstrated how technology improves mathematics teaching and learning. In South Africa, the mathematics curriculum has been aligned with science and technology to strengthen formal education and improve teacher competencies (Le, 2010). In Australia, the use of ICT in mathematics classrooms has made students more proactive, helping to overcome barriers to learning (Voss et al., 2023). In Singapore, technology integration has been linked to improved student performance (Goh et al., 2024). Similarly, in Korea and Zimbabwe, teachers' innovations in instructional media have significantly influenced student engagement and achievement (Lee & Shin, 2023; Polly, 2017).

Beyond technical mastery, digital-age learners are also expected to develop social and communication skills that allow them to engage actively in class. These competencies help students present content, manage their time, and collaborate effectively. Miller and Bernacki (2019) emphasize that self-regulated learning is key to developing a theoretical understanding of mathematics applicable to real-world contexts. Students must be able to plan, monitor, and evaluate their learning processes to achieve optimal results (Göller et al., 2024; Rosnelli & Ristiana, 2023). However, motivating students through verbal instruction alone remains a challenge (Rosnelli, 2024).

Research has shown that enjoyable, engaging experiences—particularly when supported by gamification and ICT—can foster motivation and deepen mathematical understanding (Rosnelli et al., 2024). Students trained to evaluate tasks, set goals, apply cognitive strategies, and reflect on their progress tend to perform better (El et al., 2024; Rosnelli & Ristiana, 2023). ICT tools provide

personalized learning by offering differentiated questions and real-time feedback (Göller et al., 2024), and have been shown to improve outcomes compared to conventional instruction (Fathurrohman et al., 2021; Miller & Bernacki, 2019). They also promote collaboration and shared problem-solving experiences (Abrori et al., 2024; Weinhandl et al., 2024), and are highly compatible with project- and problem-based learning models (Charalambous & Charalambous, 2023; Dahl, 2018; Tural-Sonmez, 2023).

In Malaysia, despite efforts to enhance digital competencies in education (Chia & Zhang, 2023; Shanmugam et al., 2024), observations conducted at a tutoring center in Kepong revealed that mathematics teaching remains largely manual, with minimal integration of digital learning tools. This gap between technological potential and actual classroom practices underscores the need for accessible and engaging digital learning media.

To address this issue, the researcher developed an Augmented Reality (AR)-based learning media called "Best AR", designed to strengthen students' mathematical competence through interactive, visually rich, and adaptive features (Davenport et al., 2023). Best AR enables students to explore three-dimensional geometric objects such as cubes, cuboids, prisms, cones, cylinders, and spheres, supporting deep conceptual understanding through manipulation and visual engagement.

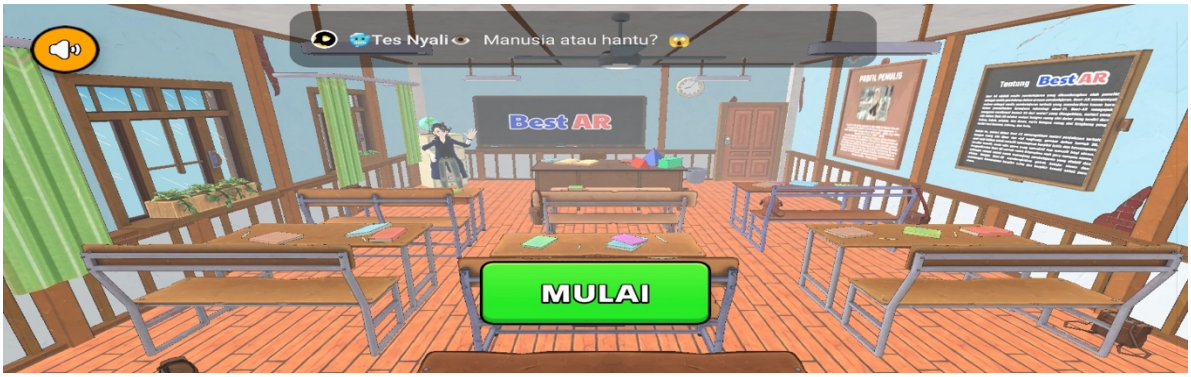

Figure 1. Best AR Learning Media Application

The media includes a range of interactive features, such as mini-games, simulations, and quizzes that align with curricular content and allow students to adjust the level of difficulty based on their abilities. These features also offer real-time feedback, facilitating self-directed learning and collaboration.

Best AR supports students in mastering key mathematical skills, particularly in geometry topics related to three-dimensional shapes. Learning outcomes include the ability to accurately apply volume formulas, interpret and describe geometrical elements such as faces, edges, and vertices, and relate abstract mathematical concepts to real-life contexts such as calculating surface area or capacity (Miller & Bernacki, 2019; Polly, 2017; Shriki & Patkin, 2016; Yulianti & Mukminin, 2021).

https://doi.org/10.30606/absis.v8i2.3253

Students using Best AR demonstrate increased motivation and confidence in tackling complex mathematical problems, supported by digital simulations and game-based experiences (Ra et al., 2019; Varas-Pavez et al., 2024). The interactive media environment enables learners to collaborate through digital platforms, visualize mathematical ideas, and engage in critical and analytical thinking (Abidin et al., 2017; Rosnelli & Ristiana, 2023).

Moreover, the integration of Best AR promotes improvement in students' logical reasoning, accuracy in mathematical operations, and problem-solving abilities. It offers a dynamic alternative to traditional methods by reducing time spent on routine calculation and allowing more focus on higher-order skills. Teachers also benefit from features such as automatic feedback and performance tracking tools (Zambak et al., 2024), supporting more efficient evaluation and individualized instruction.

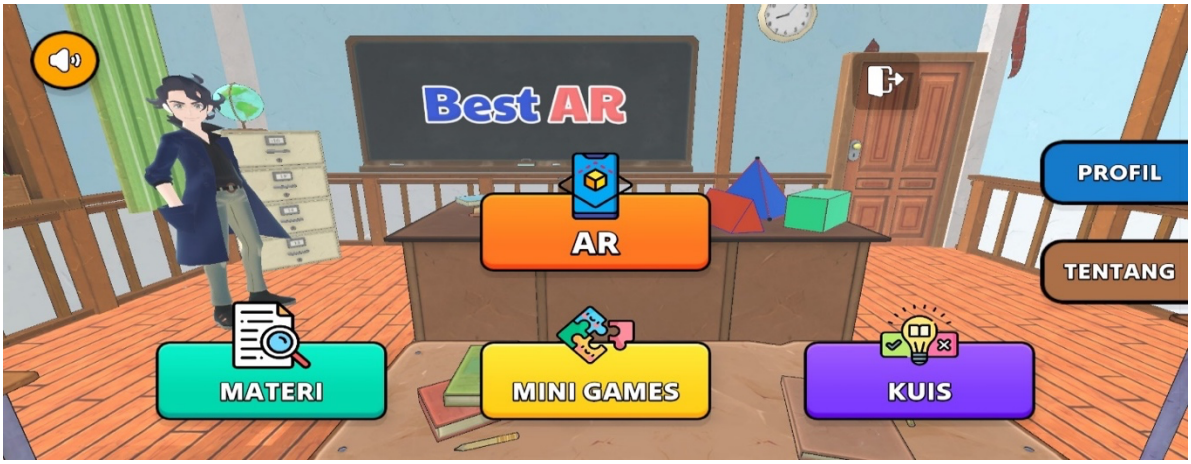

Figure 4. Scope content presented in Best AR learning media

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METHODS

This research was conducted at a tutoring center for fifth-grade elementary school students located in Kuala Lumpur, Malaysia. The study employed an exploratory qualitative design (Braun & Clarke, 2006), aiming to investigate students'

experiences in learning mathematics using the Best AR learning media developed by the researcher. The purpose of this study is to explore how this media enhances students' mathematical competence, particularly in a context where technology integration in tutoring practices remains limited. The study is considered novel due to the limited number of similar investigations in the field, especially involving the use of augmented reality in informal learning settings.

The implementation of the Best AR learning media took place in September 2024, and data collection was completed in October 2024. The participants included all five students enrolled at the tutoring center, selected using a total sampling technique. Given that the entire student population was included, the findings are considered valid and representative of the setting. Data were collected through semi-structured interviews, informal discussions, observation notes, and documentation of students' mathematics learning outcomes. This triangulation strategy ensured that the data obtained were rich, complete, and deeply reflective of the students' experiences (Bryman, 2016; Clandinin & Huber, 2010).

Semi-structured interviews were chosen to allow flexibility in exploring participants' responses and to uncover emerging themes. Each interview lasted approximately 50 to 90 minutes and was designed to elicit in-depth information regarding the use of the BEST AR media in mathematics learning. The guiding questions used during the interviews included:

1. How do students describe their experiences in using the Best AR application during mathematics learning?
2. To what extent does the Best AR media enhance students' understanding of mathematical concepts?
3. How does the Best AR media support the development of students' problem-solving skills in mathematics?
4. In what ways does the use of Best AR promote interaction and engagement among students during mathematics learning? And
5. How do students perceive the convenience and overall usability of the BEST AR learning media in learning mathematics?

These questions were adapted throughout the interview process to follow up on participants' unique perspectives and experiences. When no new insights were emerging during the data collection process, theoretical saturation was considered to have been reached (Russell & Kelly, 2002).

All interview data were audio-recorded and transcribed verbatim. Thematic analysis, as described by Braun and Clarke (2006), was employed to identify recurring patterns and themes in the data. The process began with repeated listening to the recordings, followed by careful transcription, initial coding, and theme development. The researcher interpreted and reconstructed the data based on emerging meanings and confirmed interpretations with each participant to ensure representational accuracy. This member-checking process supported the credibility

https://doi.org/10.30606/absis.v8i2.3253

of the findings (Mukminin et al., 2022). In addition, the researcher conducted follow-up reviews with participants to validate that the analysis accurately reflected their intended meanings (Wald et al., 2024). The accuracy of the information extracted from participants' experiences in using the Best AR media for mathematics learning was verified through reflective dialogue and mutual agreement (Ashworth, 2003; Mukminin & McMahon, 2013; Yin, 2014). All participants gave their informed consent to use their interview data in this study.

FINDING AND DISCUSSION

The implementation of the Best AR learning media allowed students to access mathematics materials anytime and anywhere, thereby enhancing learning flexibility. Field observations and interview data revealed that abstract mathematical concepts—especially those involving three-dimensional objects—became easier to understand through interactive visualizations (Bray & Tangney, 2017; Chandra & Briskey, 2012). The application also provided teachers with analytical data to monitor student progress and identify areas requiring instructional adjustment (Amam et al., 2017). This supported students in developing logical reasoning and problem-solving abilities in accordance with established learning competencies (Aliyu et al., 2021). Moreover, the presence of diverse learning resources such as exercises, quizzes, and mini-games made the learning process more engaging and comprehensive. Since the application can be accessed via mobile technology, students were able to explore mathematical concepts from various perspectives (Abidin et al., 2017).

Mini-games and quiz features embedded in the Best AR application encouraged students to experiment with different shapes and sizes and observe changes interactively (Chandra & Briskey, 2012; Cooper, 2011). These features also stimulated creative thinking by challenging students to find efficient solutions in a gamified environment. The integration of gamification and logic-based challenges promoted healthy competition and motivated students to develop innovative thinking strategies (Charalambous & Charalambous, 2023). For example, students learned geometry by designing virtual objects, creating classroom layouts, or developing scaled floor plans—activities that helped connect abstract geometry with real-life applications (Tural-Sonmez & Erbas, 2023; Weinhandl et al., 2024).

One participant stated that learning with Best AR made them more enthusiastic and improved their understanding of mathematical concepts. According to the student, the teacher's detailed guidance enhanced their ability to use the application, which in turn facilitated comprehension and enjoyment in solving mathematics problems. They also emphasized that the application supported visualization and calculation, especially when working with flat and curved 3D shapes. This experience marked a shift from traditional methods, demonstrating that learning mathematics could be both effective and enjoyable.

Another student explained that their conceptual understanding improved after using the AR-based mini-games to compare the volume of 3D objects. By analyzing

differences between shapes with similar heights but varying dimensions, students reported becoming more focused on mathematical analysis and more critical in problem solving. This aligns with the goal of promoting higher-order thinking through visual and interactive learning tasks.

Regarding problem-solving skills, one student noted that the use of Best AR helped them become more motivated when responding to teacher-given tasks. They mentioned being able to solve volume and surface area problems more easily, particularly for both flat and curved 3D objects. The interactive nature of the application made mathematics feel more approachable and engaging.

Improvements were also seen in student interaction and engagement. A participant highlighted that the application's quiz and collaborative features encouraged active participation during virtual discussions and joint activities. The social dimension of gamified learning led students to enjoy studying mathematics together, which fostered a stronger sense of academic collaboration and peer support.

Another student emphasized that using Best AR made mathematics feel easier and faster to complete. Although initially skeptical about technology-based learning, they found the application intuitive and efficient after the teacher's explanation. They appreciated that the application reduced the time needed for manual calculations and allowed on-demand access to learning materials via mobile phones. This flexibility significantly contributed to a more positive learning experience and increased confidence in mathematics.

Overall, the results indicate that Best AR supported the development of mathematical competence by improving students' understanding of concepts, fostering problem-solving abilities, promoting engagement, and enabling more flexible and enjoyable learning experiences. These findings reinforce the potential of augmented reality to transform mathematics education through interactivity, gamification, and mobile accessibility.

The integration of technology in mathematics education requires strategic planning to ensure effective instruction and improved learning outcomes (Abidin et al., 2017). A critical factor in technology selection is the alignment of digital tools with students' learning needs and curricular objectives (Goh et al., 2024). In this study, the use of the Best AR application—designed specifically to support the teaching of three-dimensional geometric concepts—demonstrated how interactive and visually rich tools can increase engagement through built-in mini-games and quizzes. These features allowed students to visualize abstract ideas such as volume and surface area, thereby improving conceptual understanding.

Initial technology exposure through calculators and instructional videos may serve as a foundation for integrating more advanced applications such as mathematical modeling software and AR-based simulations (Habibi et al., 2024; Hidayat & Firmanti, 2024). In the current study, students utilized Best AR to explore geometric properties, manipulate 3D objects, and engage in interactive problem-solving

https://doi.org/10.30606/absis.v8i2.3253

activities. The results confirmed that students not only gained access to dynamic representations of geometric figures but were also motivated to complete tasks and share ideas with peers, consistent with the findings of Mukminin et al. (2023) and Ra et al. (2019).

The incorporation of gamification in Best AR proved particularly effective in capturing student attention and enhancing enthusiasm toward mathematics. This aligns with the learner-centered approach, where instructional delivery is personalized to accommodate diverse learning styles (Russell & Kelly, 2002; Weinhandl et al., 2024). Gamified learning tasks enabled students to progress at their own pace while receiving timely feedback, which improved retention and self-regulation (Abrori et al., 2024; Aliyu et al., 2021). Moreover, the application's 3D visualizations helped demystify abstract content, supporting findings by Davenport et al. (2023) and Göller et al. (2023).

Teacher guidance remained essential during implementation. Students relied on instructional support to navigate application features, such as video tutorials and simulations, before independently solving geometry-based problems (Chandra & Briskey, 2012; Fathurrohman et al., 2021). The application's step-by-step feedback and real-time rendering of geometric solids—cubes, pyramids, spheres, cones, and cylinders—facilitated a flexible, mobile learning experience beyond the classroom environment (Hidayat & Firmanti, 2024; Lebeničnik & Istenic, 2024).

The study also highlighted Best AR's role in enhancing collaborative learning. Through shared tasks and group projects, students exchanged ideas and problem-solving strategies, reinforcing peer learning (Amam et al., 2017; Abrori et al., 2024). This collaborative dimension was further strengthened by narrative animations and interactive features that supported visual, auditory, and kinesthetic learning styles (Charalambous & Charalambous, 2023; El Bedewy et al., 2024). Teachers facilitated this process by guiding students in team-based assignments and encouraging equitable participation, even among more reserved learners (Cooper, 2011; Davenport et al., 2023).

The Best AR application also contributed to students' cognitive development. By engaging in low-pressure, exploratory environments, students practiced monitoring their progress and applying logical, critical, and analytical thinking (Lee & Shin, 2023; Miller & Bernacki, 2019; Rosnelli & Ristiana, 2023). Visualizing complex mathematical problems fostered innovation and deeper conceptual connections, consistent with the findings of Bray & Tangney (2017) and Chandra & Briskey (2012). Additionally, the use of project-based learning tasks—such as designing scaled floor plans or modeling 3D parks—encouraged students to make data-driven decisions and reflect on real-world applications of mathematics (Weinhandl et al., 2024; Zambak et al., 2024).

Despite these benefits, challenges in implementing Best AR were also observed. Limited access to digital devices and internet connectivity posed barriers to

consistent use. Some students required substantial guidance to operate the app effectively, and not all teachers were fully equipped to integrate AR technology without additional training. These findings underscore the importance of adequate infrastructure, digital literacy, and sustained professional development for successful implementation.

Nevertheless, Best AR demonstrated its potential to promote student agency and experimentation. Teachers used gamification and structured feedback to support independent learning while monitoring performance data to provide targeted support (Mukminin et al., 2022; Rosnelli & Ristiana, 2023). The app's analytical tools allowed teachers to track progress, identify misconceptions, and intervene when necessary (Charalambous & Charalambous, 2023; Amam et al., 2017).

By encouraging active participation through competition, quizzes, and collaborative design challenges, Best AR helped transform mathematics into an accessible and enjoyable subject. The application's user-friendly interface and adaptive features supported diverse learners, reinforcing the notion that technology, when thoughtfully integrated, can bridge the gap between abstract content and meaningful student experiences.

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings, the use of Best AR learning media significantly enhanced students' mathematical competence, particularly in understanding three-dimensional objects. The application enabled students to visualize abstract geometric shapes—such as cubes, prisms, cones, and spheres—through simulations, animations, quizzes, and mini-games. These features supported deeper conceptual understanding and allowed students to engage actively in solving mathematics problems presented by the teacher. The learning atmosphere became more enjoyable, enabling students to adapt to various levels of question difficulty based on their individual abilities.

The flexibility of Best AR, which allows students to access learning materials anytime and anywhere via mobile devices, contributed to increased autonomy and motivation. Students could study at their own pace, which helped develop their problem-solving skills and fostered a more personalized learning experience. The application's integration with gamified elements further stimulated students' interest and motivation to explore mathematical content.

This research implies that well-designed AR-based learning media, when aligned with the curriculum and mathematical competence standards, can support teachers in delivering more engaging and effective mathematics instruction. Moreover, the Best AR app demonstrates potential as a scalable learning tool that addresses both cognitive and affective domains in mathematics education. Its use can help overcome students' negative perceptions of mathematics by making the subject more accessible, interactive, and enjoyable.

https://doi.org/10.30606/absis.v8i2.3253

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