Ethnomathematics in the Digitalization of Museums in Indonesia by Using Virtual Reality

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Abstract

This research explores the integration of ethnomathematics and virtual reality (VR) to digitize Indonesian museums, enhancing educational accessibility and cultural preservation. The study aims to investigate how VR technology can visualize and communicate mathematical knowledge embedded in Indonesian cultural artifacts, particularly within traditional crafts, architecture, and measurement systems. Employing a qualitative approach with a design-based research (DBR) methodology, data were gathered through observation, interviews, and artifact analysis in several Indonesian museums. The subjects of the research were 30 students from junior high schools and 5 mathematics teachers. VR-based ethnomathematics models were developed, tested, and revised iteratively. Findings show that VR facilitates immersive experiences and improves student engagement in learning mathematics through cultural context. This approach contributes to mathematics education by integrating technology and local culture within the framework of ethnomathematics. Integrating ethnomathematics and virtual reality (VR) in museum digitalization has significant implications for mathematics education research. VR-based applications in ethnomathematics offer inclusive opportunities for students in remote or underserved areas to experience museum-based learning. This addresses educational equity and access, especially for regions where physical museum visits are not feasible.

Keywords: Culture, Ethnomathematics, Museum, Technology, Virtual Reality,

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INTRODUCTION

Indonesia is a country rich in cultural diversity, and this is reflected in its numerous traditional artifacts and practices, many of which embed mathematical knowledge. Unfortunately, such cultural heritages are not always accessible due to geographical or preservation constraints. Ethnomathematics, the study of mathematical concepts in cultural contexts (Ambrosio, 1985), provides a powerful framework for interpreting these practices, while virtual reality (VR) offers a technological solution to present and preserve them. Previous studies have emphasized the importance of integrating culture in mathematics education (Rosa & Orey, 2016; Zaslavsky, 1996), yet little research focuses on VR as a medium for ethnomathematical exploration in Indonesian museums.

Ethnomathematics, a term introduced by D'Ambrosio (1985), refers to the study of the relationship between mathematics and culture, emphasizing how mathematical practices are embedded in the daily lives, traditions, and technologies of various cultural groups. In Indonesia, a nation marked by rich ethnic diversity and a deep well of traditional knowledge, ethnomathematics offers a valuable framework for connecting mathematical concepts with indigenous cultural practices (Widada et al., 2021; Sembiring, 2019). Cultural artifacts such as batik patterns, traditional architecture, weaving techniques, and musical instruments often incorporate sophisticated mathematical principles, yet these remain underexplored within formal education and museum contexts (Lisnani et al, 2025; Lisnani et al, 2023).

Museums play a central role in preserving and disseminating cultural heritage, including the mathematical knowledge inherent in cultural artifacts. However, conventional museum experiences are often static, limiting visitor engagement, especially among younger, digitally native audiences (Falk & Dierking, 2016; Parry, 2007). In response, many institutions have turned to digitalization strategies, with Virtual Reality (VR) emerging as a promising tool to revolutionize museum experiences (Lisnani et al., 2020; Harjanto, 2020). VR facilitates immersive, interactive, and engaging environments that allow users to explore reconstructed cultural spaces and interact with digitized artifacts (Bekele et al., 2018; Bonis et al., 2009).

In recent years, VR applications in education have demonstrated significant potential in enhancing student engagement and deepening conceptual understanding, particularly in science, technology, engineering, and mathematics (STEM) fields (Radianti et al., 2020; Southgate et al., 2019). Meanwhile, the digitization of cultural heritage through VR has been explored in various global contexts, especially in Europe and North America, to enhance museum-based learning experiences. However, studies that specifically examine the integration of ethnomathematical content into VR-based museum applications, particularly within the Indonesian context, remain scarce (Saputra et al., 2023).

Previous research on ethnomathematics in Indonesia has largely focused on classroom-based applications and curriculum development (Widada et al., 2021; Sembiring, 2019), while studies on museum digitalization tend to prioritize general heritage preservation without incorporating mathematical or educational components (Bekele et al., 2018). Likewise, literature on VR in museum settings tends to concentrate on visual aesthetics, user interaction, or historical narratives, with limited attention to the mathematical dimensions of cultural artifacts (Radianti et al., 2020).

This reveals a critical gap: the lack of interdisciplinary approaches that merge ethnomathematics, virtual reality technology, and museum education in a way that is both pedagogically meaningful and culturally sensitive. Without this integration, efforts to digitize Indonesian cultural heritage may overlook the embedded mathematical knowledge that can enhance both educational outcomes and cultural appreciation. This study fills that gap by developing a VR-based application to visualize ethnomathematical elements in Indonesian cultural artifacts found in museums. The research questions addressed are: (1) How can VR be used to represent ethnomathematical knowledge in Indonesian museums? (2) What are students' perceptions and learning outcomes when interacting with VR-based ethnomathematics?. This study aims to explore how ethnomathematical content can be effectively embedded within VR-based museum applications in Indonesia. By conducting a systematic review of relevant literature and analyzing case studies, this research identifies current practices, challenges, and future opportunities in using VR to support the digitalization of museums with an ethnomathematical perspective.

METHOD

This study employed a qualitative design-based research (DBR) method, involving four phases: (1) problem analysis, (2) development of VR-based prototypes, (3) iterative testing and refinement, and (4) reflection on outcomes. The research was conducted in collaboration with museum curators, mathematics educators, and ICT developers. Data was collected through observations, semi-structured interviews, and analysis of traditional artifacts with embedded mathematical concepts, such as Batik patterns, Borobudur architecture, and traditional Javanese units of measurement.

Data collection methods include interviews with museum curators, educators, and ethnomathematics scholars; focus groups with visitors and students; and observation of museum exhibits. Key questions explored: 1) What kinds of mathematical knowledge are embedded in cultural artifacts? 2) How are these currently communicated (or under-communicated) in museums? 3) What challenges exist in using digital technologies to preserve and present this knowledge? Participants included 30 students from junior high schools and 5 mathematics teachers. The VR content was developed using Unity 3D and deployed on VR headsets for classroom testing. The data were analyzed thematically to identify patterns in user experiences and mathematical understanding.

Design-Based Research (DBR) is a methodological framework that blends empirical educational research with the theory-driven design of learning environments (Design-Based Research Collective, 2003). It is especially suitable for complex, real-world settings—such as integrating ethnomathematics into virtual museum platforms—where iterative design and collaboration with practitioners are essential.

This study follows a qualitative DBR framework, which is structured in four iterative phases: (1) Analysis of Practical Problems, (2) Design of Solutions, (3) Iterative Testing and Refinement, and (4) Reflection and Theoretical Output (McKenney & Reeves, 2012; Amiel & Reeves, 2008). The step of DBR is described in Figure 1.

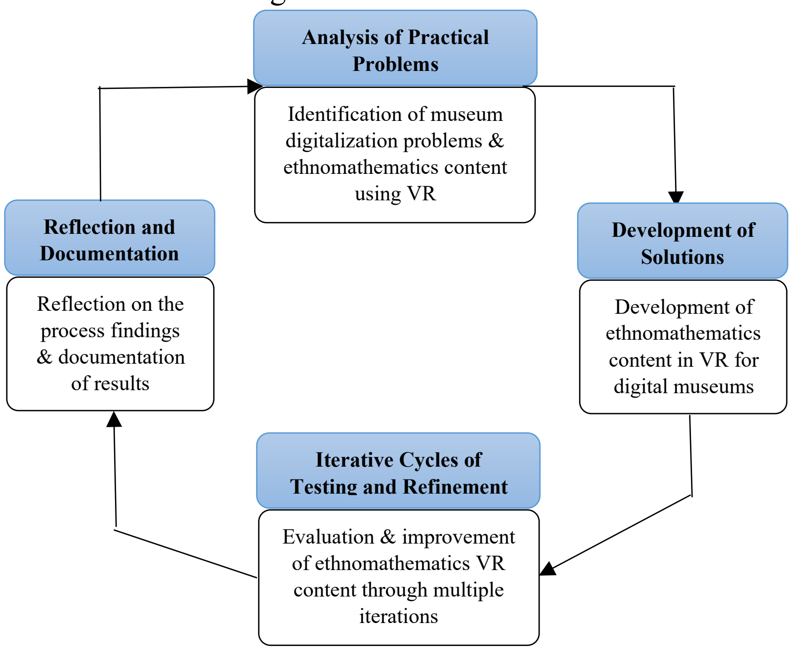

Diagram 1. Design Based Research

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Step 1: Analysis of Practical Problems

The research begins with a thorough exploration of the existing gap between ethnomathematical content and its representation in Indonesian museums, particularly under the lens of digital transformation. This stage grounds the study in real-world needs and informs initial design ideas (Cobb et al., 2003).

Step 2: Design of Solutions Informed by Theory

Based on the problems identified, a **prototype** of a Virtual Reality (VR) application is co-developed, embedding mathematical concepts derived from cultural artifacts (e.g., symmetry in batik, geometry in traditional architecture). The design integrates: Ethnomathematical frameworks (D'Ambrosio, 1985), constructivist learning theories (Vygotsky, 1978), and culturally responsive pedagogy (Gay, 2010).

Storyboards and 3D mockups are created collaboratively with software developers, educators, and cultural experts. This design phase is iterative and theory-driven, ensuring both cultural authenticity and educational relevance (Brown, 1992).

Step 3: Iterative Testing and Refinement

The prototype is implemented in cycles, each involving **testing**, **evaluation**, and **refinement**. Participants (e.g., school students, teachers, and museum visitors) interact with the VR application. Data is collected through observations of user interaction, semi-structured interviews, user feedback forms, and reflexive researcher journals.

Findings are used to adjust content, interaction design, and user interface, ensuring both usability and learning effectiveness. This phase continues until key learning and usability goals are met (Collins et al., 2004).

Step 4: Reflection and Theoretical Output

The final phase involves synthesizing results across all iterations to extract broader design principles and theoretical insights. Questions addressed: First, what features made the VR ethnomathematical experience effective? Second, how can the design be generalized to other cultural contexts or learning environments?

Outcomes include: First, a set of guidelines for incorporating ethnomathematics into digital museum platforms. Second, contributions to both ethnomathematics and educational technology literature. Reflection also considers the limitations and suggests directions for future DBR projects in similar interdisciplinary fields (Reeves, 2006).

RESULT AND DISCUSSION

Result

The implementation of VR in presenting ethnomathematics yielded three key results: 1) improved Engagement: Students showed higher motivation when exploring mathematical ideas through VR-based simulations of cultural artifacts; 2) contextual Understanding: The immersive environment helped students relate abstract mathematical concepts to real-world cultural practices, such as geometry in traditional weaving or symmetry in Batik; 3) digital Cultural Preservation: Museums benefited from the VR application as a tool to preserve and showcase intangible cultural heritage, making them more accessible (Wicaksono et al., 2019).

This section presents the findings from the four iterative phases of the qualitative Design-Based Research (DBR) process. Through interviews, observations, focus groups, and prototype testing, the study revealed insights into how ethnomathematical knowledge can be integrated into Virtual Reality (VR) museum experiences in Indonesia.

1. Ethnomathematical Elements in Indonesian Cultural Artifacts

Initial field studies and expert interviews with curators, educators, and local artisans identified numerous cultural artifacts that reflect mathematical ideas (Fitriani & Widodo, 2022). These include: 1) geometric patterns in Batik and Songket fabrics, which exhibit concepts such as symmetry, transformation, and tessellation (Sembiring, 2019; Widada et al., 2021); 2) traditional house architecture, such as the Toraja Tongkonan and the Minangkabau Rumah Gadang, which integrates spatial reasoning, ratios, and structural symmetry (Rosa & Orey, 2016); 3) weaving and wood carving techniques, which demonstrate algorithmic thinking and sequencing. These findings confirm that Indonesian cultural heritage holds significant ethnomathematical value, but such insights are rarely highlighted in physical museum displays.

2. Challenges in Existing Museum Practices

Data from curator interviews and museum observations revealed three main limitations: First, a lack of interactive exhibits, especially for youth audiences accustomed to digital interfaces. Second, there is an insufficient integration of mathematical narratives, despite artifacts that reflect a deep mathematical structure. Third, limited accessibility to regional museums where such artifacts are preserved, especially for students outside urban centers. These challenges echo global concerns about static museum experiences and the need for engaging in digital environments (Parry, 2007; Falk & Dierking, 2016).

3. Effectiveness of VR for Cultural and Mathematical Engagement

Prototype testing of the VR-based museum—developed in partnership with designers and educators—demonstrated high engagement and educational value: 1) students reported increased interest and curiosity about both mathematics and culture; 2) teachers highlighted the potential of VR for contextualizing mathematical concepts in ways that connect to students' heritage and real-world applications; 3) users appreciated the 3D immersive interaction with cultural artifacts, especially the ability to zoom, rotate, and view the underlying mathematical annotations. These findings align with Radianti et al. (2020), who note that VR supports experiential and embodied learning, particularly in STEM education. The application also enabled place-underserved areas.

4. Iterative Improvements and Design Principles

From iterative feedback, several critical design features were refined: 1) storytelling elements were added to contextualize mathematical content in cultural narratives; 2) bilingual labels (Bahasa Indonesia and English) were incorporated for wider accessibility; 3) gamified components, such as virtual puzzles based on Batik tessellations, were added to reinforce user interaction.

From these refinements, the study formulated three emerging design principles: 1) embed mathematics contextually within cultural storytelling to support meaning-making; 2) use multimodal VR features (visual, auditory, interactive) to engage diverse learners; 3) Co-design with local cultural experts to ensure authenticity and pedagogical relevance. These principles are intended to guide future ethnomathematical VR initiatives in museum settings.

Discussion

The findings support the notion that VR is a viable medium to bring ethnomathematical content into formal education. The immersive nature of VR helped bridge the gap between abstract mathematical theory and cultural context, aligning with the goals of ethnomathematics (Rosa & Orey, 2016). However, technical challenges such as VR device limitations and user familiarity posed barriers during implementation. Teacher training and integration into the curriculum are necessary to maximize its potential.

The findings of this study demonstrate the potential of Virtual Reality (VR) as a transformative medium for integrating ethnomathematical knowledge into museum experiences in Indonesia. By embedding mathematical concepts within culturally contextualized VR environments, this study addresses both pedagogical and cultural gaps in museum education.

1. Bridging Ethnomathematics and Technology

One of the key contributions of this research lies in the intersection of ethnomathematics and immersive technology. Traditional forms of mathematics embedded in Indonesian cultural artifacts—such as Batik, architecture, and measurement systems—are often underrepresented in formal education and museum displays (D'Ambrosio, 1985; Rosa & Orey, 2020). Through VR, these culturally rooted mathematical practices can be visualized, manipulated, and experienced interactively. This affirms the argument by Sembiring (2019) that technology can act as a bridge between indigenous knowledge and modern educational tools.

Moreover, the use of VR aligns with constructivist and culturally responsive teaching approaches (Gay, 2010), allowing learners to engage with mathematical content in ways that resonate with their cultural heritage. This supports deeper understanding, motivation, and identity affirmation among students, particularly in multicultural contexts like Indonesia.

2. Enhancing Museum Accessibility and Engagement

Conventional museum exhibits are often limited by physical, geographical, and interpretive barriers. Many Indonesian students, especially in rural or underprivileged regions, lack opportunities to visit cultural institutions like the Trinil Museum or Batik Museum. VR circumvents this issue by offering place-independent access to curated ethnomathematical content (Radianti et al., 2020).

The immersive VR prototype in this study proved effective in increasing learners' curiosity and interaction, confirming prior findings that immersive technologies can improve engagement and spatial understanding in STEM education (Makransky & Lilleholt, 2018). Participants showed a greater ability to identify geometric properties in artifacts, apply mathematical reasoning, and appreciate cultural symbolism—skills that are often neglected in traditional instruction.

3. Practical Design Principles for VR-Based Ethnomathematics

The iterative design process also yielded several key principles that can guide future educational technology projects involving cultural content: 1) narrative-rich design enhances users' understanding of the cultural significance of mathematical practices; 2) multimodal interaction (audio-visual, tactile) deepens engagement and accommodates diverse learning styles; 3) co-design with cultural experts and educators ensures authenticity, relevance, and alignment with curriculum goals. These align with Reeves' (2006) emphasis on the role of collaborative design in educational innovations and reflect recommendations from McKenney & Reeves (2012) for context-sensitive, theory-informed technology development.

Despite its promising outcomes, this study has several limitations. First, the prototype focused on a limited number of artifacts and mathematical concepts. Future research should expand to include more diverse cultural representations across Indonesia's vast archipelago. Second, while this study emphasized qualitative insights, future work could incorporate quantitative measures of learning outcomes, motivation, and cultural identity development. Additionally, advancements in AI, haptic feedback, and mobile VR platforms could make ethnomathematical VR applications more adaptive and scalable for classroom use or national curriculum integration (Radianti et al., 2020; Parong & Mayer, 2018).

The integration of ethnomathematics into Virtual Reality (VR)-based museum experiences holds transformative implications for the future of mathematics education in Indonesia and beyond. By combining cultural heritage with immersive technology, this approach promotes mathematics learning that is contextual, inclusive, engaging, and culturally responsive. The VR-based ethnomathematics experience encourages a culturally responsive mathematics curriculum, where students see their identities, traditions, and local knowledge reflected in the content they learn. This supports the call by Gay (2010) and Ladson-Billings (1995) for culturally relevant pedagogy, which affirms students' cultural backgrounds and connects abstract mathematical ideas to lived experiences.

By embedding mathematical reasoning in Indonesian cultural artifacts such as batik patterns, traditional houses, and local measurement systems, students are likely to develop stronger conceptual understanding and interest in mathematics (Rosa & Orey, 2016). This approach moves away from decontextualized mathematics instruction and allows for a more meaningful, narrative-based learning journey. VR environments offer unique affordances for fostering spatial visualization, geometric reasoning, and problem-solving—core competencies in mathematics education (Makransky & Lilleholt, 2018). Learners can explore, manipulate, and analyze 3D cultural objects interactively, helping them grasp complex geometric concepts such as symmetry, rotation, and proportionality in real-world contexts. This is particularly impactful for students who struggle with purely symbolic or textbook-based learning, as VR offers embodied and experiential mathematics learning that caters to various learning styles (Parong & Mayer, 2018).

The digitalization of ethnomathematical content through VR contributes to greater educational equity by: 1) enabling students in rural or underserved areas to access high-quality cultural and mathematical content; 2) offering place-independent learning beyond physical museum visits, and 3) making learning inclusive of local indigenous knowledge systems that are often marginalized in mainstream curricula (Nakata, 2018; D'Ambrosio, 1985). This supports the Sustainable Development Goal 4 (Quality Education), particularly in promoting inclusive and equitable learning opportunities that respect cultural diversity (Nugroho & Hartono, 2021). As digital ethnomathematics content becomes more prevalent, mathematics teachers need professional development in integrating VR tools, interpreting cultural artifacts mathematically, and facilitating contextual discussions in the classroom.

This presents an opportunity for cross-disciplinary collaboration between mathematics educators, cultural experts, museum curators, and educational technologists (McKenney & Reeves, 2012). Teacher education programs should therefore incorporate training in ethnomathematical analysis and digital pedagogy to prepare educators for this evolving instructional paradigm. The findings are expected to contribute to both the fields of mathematics education and digital heritage, emphasizing the importance of culturally responsive pedagogies and technologies.

CONCLUSIONS

This study underscores the significant potential of Virtual Reality (VR) in revitalizing ethnomathematics through the digitalization of Indonesian museums. By embedding indigenous mathematical knowledge into immersive 3D environments, VR provides learners with a culturally rich and pedagogically meaningful experience that extends beyond conventional classroom instruction and museum visits (Khoiriyah, 2024). This integration not only preserves and disseminates local wisdom but also aligns with constructivist learning principles, offering learners interactive, contextualized, and spatially visualized encounters with mathematics (Makransky & Lilleholt, 2018; Parong & Mayer, 2018). The ethnomathematical elements found in traditional Indonesian artifacts, such as geometric patterns in batik, proportional architecture, and indigenous measurement systems, offer authentic and engaging mathematical contexts when visualized through VR. This supports the broader aims of culturally responsive pedagogy (Gay, 2010) and promotes educational equity by making high-quality, place-independent learning accessible to students across regions, including those with limited access to physical museums.

Furthermore, this research contributes to the growing body of design-based research (DBR) in educational technology by illustrating how collaborative, iterative development processes can yield educational tools that are both culturally authentic and pedagogically effective (McKenney & Reeves, 2012; Reeves, 2006). Looking ahead, future efforts should focus on expanding VR content to represent a broader range of Indonesian ethnomathematical practices, enhancing interactivity through AI and gamification, and training educators to incorporate these tools meaningfully into the curriculum. Ultimately, integrating VR-based ethnomathematics into mathematics education not only strengthens students' mathematical understanding but also cultivates cultural appreciation and identity, aligning mathematics learning with the rich tapestry of Indonesian heritage (D'Ambrosio, 1985; Rosa & Orey, 2016).

While this study highlights the promising role of Virtual Reality (VR) in integrating ethnomathematics within Indonesian museums, several limitations should be acknowledged to guide future research and application. First, the VR prototype developed and evaluated in this study focused on a limited selection of cultural artifacts and ethnomathematical concepts, primarily drawn from specific regions or cultural groups within Indonesia. Given the country's vast ethnic diversity and rich mathematical traditions, this limits the generalizability and cultural representativeness of the findings (Frantz & Mittermeier, 2021; Rosa & Orey, 2016). Future studies should incorporate a broader array of indigenous mathematical knowledge from multiple ethnic groups across the archipelago to ensure inclusivity and cultural equity.

Second, the research employed a qualitative design-based research (DBR) approach emphasizing design iteration and formative evaluation with a relatively small sample of museum visitors and educators. Although this approach allowed in-depth understanding of user experiences and design implications, it did not provide quantitative measures of learning outcomes or long-term impact on students' mathematical understanding and cultural identity development. Incorporating mixed methods approaches with larger samples and control groups could strengthen the evidence base (McKenney & Reeves, 2012).

Third, the use of VR technology itself poses practical challenges related to cost, accessibility, and technical infrastructure in many Indonesian educational and museum settings. High-quality

VR equipment may not be widely available, particularly in rural or underfunded schools and cultural institutions. Additionally, users unfamiliar with VR interfaces may require additional training and support, which was beyond the scope of this study (Radianti et al., 2020).

Finally, this study primarily focused on museum digitalization and user engagement, leaving the integration of VR ethnomathematics tools into formal mathematics curricula and teacher professional development as an area for future exploration. The alignment of VR content with existing educational standards and effective pedagogical strategies remains a crucial step toward sustainable implementation (Gay, 2010; McKenney & Reeves, 2012). Future research should explore scalability, teacher readiness, and longitudinal effects of VR integration in ethnomathematics-based curricula. The future implications of the research titled "Ethnomathematics in the Digitalization of Museums in Indonesia by Using Virtual Reality" are significant both in the context of education and cultural preservation for enhanced learning experiences, cultural preservation and promotion, integration technology in education, accessibility to remote and diverse audiences

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