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Bridging Cultural Contexts and Digital Innovation in Mathematics Learning: A Meta-Analytic of Augmented Reality Supported Ethnomathematics

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ABSTRACT

The integration of cultural perspectives into Mathematics Education has expanded significantly alongside the rapid development of Augmented Reality (AR). While prior reviews have separately examined digital innovation in mathematics learning or the role of ethnomathematics in culturally responsive pedagogy, no previous meta-analysis has systematically synthesized empirical evidence at the intersection of augmented reality and ethnomathematics. This study addresses that gap by providing the first quantitative synthesis of the effectiveness of AR-supported ethnomathematics across educational levels, thereby bridging cultural context and digital innovation within a single analytical framework. Using a meta-analytic approach, quantitative findings from 21 empirical studies (selected from an initial pool of 101 studies indexed in Google Scholar and Scopus) were synthesized using a random-effects model in Comprehensive Meta-Analysis (CMA). The overall effect size was large and positive (ES = 1.10), demonstrating that AR-supported ethnomathematics substantially improves students' mathematics learning outcomes compared to conventional approaches. Moderator analyses revealed significant heterogeneity, with stronger effects observed in interventions that integrated interactive and contextually immersive AR features and at the primary and secondary education levels. The magnitude of the effect (ES = 1.10) indicates not merely statistical significance but strong practical relevance, suggesting that integrating culturally grounded mathematical contexts with immersive AR technology can meaningfully enhance conceptual understanding, engagement, and knowledge retention. For curriculum development, these findings support the systematic incorporation of AR-based ethnomathematical modules into mathematics syllabi, particularly in culturally diverse settings. Rather than positioning digital innovation as a supplementary tool, the results advocate for its structural integration into culturally responsive curriculum design. Future research should employ longitudinal and mixed-method designs to examine the sustainability of these effects and to explore how evolving digital innovations influence students' cognitive and affective learning trajectories over time.

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A. INTRODUCTION

Innovation in mathematics learning is a key requirement in addressing the challenges of 21st-century education (Rohmah et al., 2024; Rosidin et al., 2025; Tamur et al., 2025), particularly in creating meaningful, contextual, and adaptive learning to technological developments (Tamur et al., 2026). The development of digital innovation has opened up new space for the transformation of mathematics pedagogy that focuses not only on procedures but also on the meaning of concepts (Beck et al., 2020; Meesook et al., 2024; Ruslau et al., 2025). In this context, the integration of local culture through an ethnomathematics approach is increasingly relevant as a contextual and learner-centered learning strategy (Ayu et al., 2023; Kariadinata et al., 2023; Tamur et al., 2025). Augmented reality (AR) has emerged as a potential form of digital innovation to bridge culture and mathematical representation visually and interactively. Therefore, examining the role of AR-based digital innovation in ethnomathematics is a strategic issue in the development of modern mathematics learning.

Conceptually, ethnomathematics emphasizes that mathematical knowledge is inseparable from the cultural context, social practices, and life experiences of society (Deda, Disnawati, et al., 2024; Komaladewi et al., 2024; Malalina et al., 2020; Subaryo et al., 2024; Tamur et al., 2020). This approach views culture as an authentic and meaningful learning resource, thereby enhancing students' connection to mathematical material (Deda, Rosa, et al., 2024; Malalina et al., 2022; Permita et al., 2022; Tamur, Wijaya, et al., 2023). However, in practice, the implementation of ethnomathematics often faces limitations in visualization and abstraction of concepts. Digital innovation, particularly augmented reality, offers a solution by presenting cultural objects in the form of immersive mathematical representations. Thus, the integration of AR in ethnomathematics has the potential to strengthen students' conceptual understanding and learning experiences.

Augmented reality, as a digital innovation in education, has been shown to increase student interaction, motivation, and cognitive engagement (Pangestu et al., 2024; Tamur et al., 2024, 2026; Tamur, Ngao, et al., 2025; Yilmaz & Batdi, 2021). This technology enables the simultaneous integration of the real and virtual worlds, thus supporting exploration-based learning and hands-on experience (Mendez & Aviles, 2025). In mathematics learning, AR can facilitate the visualization of abstract concepts that have historically been a major difficulty for students (Arnoldus et al., 2025; Tamur et al., 2026; Tamur, Ngao, et al., 2025). When AR is combined with a cultural context, learning becomes not only technological but also has social and cultural meaning (Tamur et al., 2026). This strengthens AR's position as a relevant digital innovation within the framework of contextual mathematics learning.

Although various empirical studies have reported the positive impact of AR on ethnomathematics learning (e.g., Muwahiddah et al., 2021; Nugroho, 2024; Nurhasanah et al., 2023; Pasaribu et al., 2024), these findings remain fragmented. Differences in research design, type of digital innovation, and educational level lead to significant variation in results. This situation makes it difficult for researchers and education practitioners to draw comprehensive conclusions regarding the effectiveness of ethnomathematics-based AR. Furthermore, few studies explicitly place digital innovation as a central characteristic of learning interventions. Therefore, a systematic empirical synthesis is needed to provide a comprehensive picture of the impact of this approach.

Meta-analysis is an appropriate methodological approach for integrating empirical findings from various primary studies (Juandi et al., 2021; Tamur, 2021; Tamur et al., 2021; Wijaya et al., 2022). Through meta-analysis, the strength of an intervention's effect can be estimated quantitatively and more objectively (Juandi & Tamur, 2020, 2021; Pigott & Polanin, 2020; Tamur, Juandi, et al., 2023). This approach also allows for the identification of moderating factors contributing to variation in research results (Suparman et al., 2021; Tamur & Juandi, 2020). In the context of mathematics learning, meta-analysis has been widely used to evaluate the effectiveness of various pedagogical and technological innovations. However, meta-analyses specifically examining AR-supported ethnomathematics with an emphasis on digital innovation are still very limited.

The novelty of this research lies in placing digital innovation as the central character in analyzing the effectiveness of augmented reality-based ethnomathematics learning. This study not only measures the overall impact on mathematics learning outcomes but also analyzes the variation in effects based on the type of digital innovation used. Furthermore, differences in educational level are considered as a moderating factor that could potentially explain the heterogeneity of results. With this approach, the research is expected to provide deeper theoretical and empirical contributions, while also broadening the discourse on the integration of culture and technology in mathematics education. Practically, the results of this study are expected to inform decision-making for educators and curriculum developers. A comprehensive understanding of the effectiveness of AR in ethnomathematics can encourage the more targeted and sustainable implementation of digital innovation. Furthermore, the research findings can be used as a reference in developing learning designs that are responsive to local cultural contexts. The integration of digital innovation and culture also aligns with the principles of meaningful and inclusive learning. Thus, this research has broad implications for mathematics education practice.

Based on this description, this study aims to systematically synthesize empirical evidence regarding the effectiveness of mathematics learning supported by ethnomathematics-based digital innovation. The primary objective of this study is to obtain a comprehensive quantitative estimate of the impact of this approach on students' mathematical abilities. To achieve this goal, this study was designed to answer two main research questions. First, to what extent does learning supported by digital innovation and ethnomathematics impact students' mathematical abilities? Second, to what extent do educational level and type of digital innovation influence the magnitude of the resulting learning effect?

B. METHODS

1. Research Design

This study applies a meta-analysis design as a methodological framework to integrate and synthesize empirical results related to the effects of ethnomathematics learning supported by augmented reality technology on students' mathematical abilities. This approach allows for the integration of findings from various primary studies conducted in diverse educational contexts and with diverse student characteristics (Juandi, 2021). By compiling quantitative data from multiple studies, meta-analysis provides more accurate and reliable effect size estimates than individual analyses. Furthermore, this design allows researchers to evaluate the consistency of findings and identify variations in effects across studies.

2. Search Strategy

A systematic literature search was conducted in several reputable academic databases, including Scopus, Web of Science, ERIC, ScienceDirect, and Google Scholar, covering publications from January 2013 to December 2025. The search strategy was designed using a combination of keywords representing three main domains: ethnomathematics, augmented reality, and mathematics education, linked through Boolean operators (e.g., "ethnomathematics" AND "augmented reality" AND "mathematics education," and "culturally based mathematics" AND "AR"). This approach aims to ensure the accessibility of relevant and comprehensive empirical studies. To maintain the methodological quality and validity of the findings, gray literature sources such as theses, conference proceedings, and non-peer-reviewed reports were excluded from the analysis.

3. Inclusion Criteria

Studies were included in this meta-analysis if they met a number of strictly defined inclusion criteria. First, studies had to explicitly examine the integration of ethnomathematics approaches with augmented reality and supported by digital innovations, such as the use of mathematical software or technology-based applications, in the context of formal mathematics education. Studies that implemented similar technologies but did not focus on mathematics learning, as reported by Arymbekov et al. (2023), were excluded from the analysis. Second, studies had to use experimental or mixed-method designs that produced measurable outcomes related to students' mathematical abilities. Therefore, meta-analyses, bibliometric analyses, and systematic literature reviews, including those conducted by Batiibwe (2024); Rohim et al. (2024); Sumarni & Mauladaniyati (2025); Tamur, Sennen, & Vaz, (2025); Tamur, Wibisono, et al. (2024); Tamur, Wijaya, et al. (2023) were excluded even though they discussed the effectiveness of augmented reality-based ethnomathematics.

Third, studies must provide sufficient statistical information, such as mean values, standard deviations, sample sizes, or effect sizes, to enable the data to be transformed into effect sizes that can be analyzed quantitatively. Therefore, studies conducted by Ayu et al. (2023) and Putra et al. (2024) were excluded because they did not provide the necessary statistical data, despite their relevance to the research topic. Fourth, only articles published in peer-reviewed scientific journals were considered to ensure the quality and validity of the findings. Fifth, included publications must be written in English or Indonesian. Studies that focused solely on ethnomathematics or augmented reality, without any integration of the two, were excluded from the analysis. The entire study selection and screening process in this research followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and methodological rigor, as presented in Figure 1.

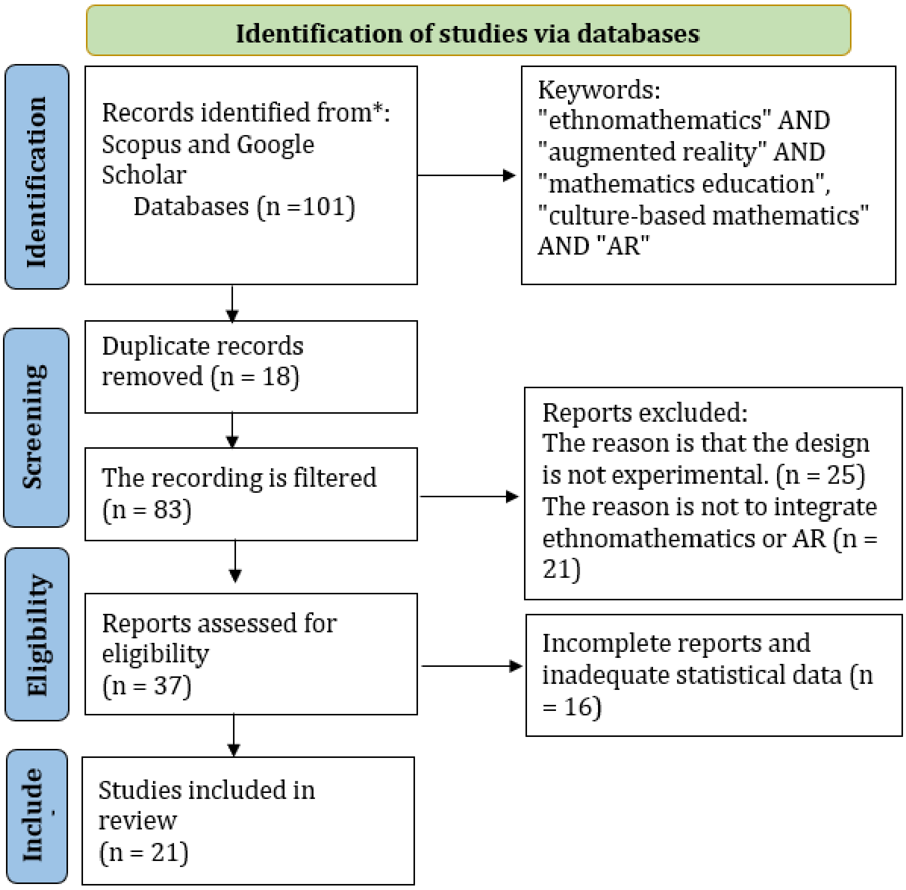

Figure 1. PRISMA procedure

The identification and selection process for primary studies in this study systematically and transparently followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. The initial identification phase yielded 101 articles retrieved from the Scopus and Google Scholar databases through a combination of keywords relevant to ethnomathematics, augmented reality, and mathematics education. After deduplication, 18 duplicate articles were eliminated, leaving 83 articles for the initial screening phase based on title and abstract. At this stage, 46 articles were excluded for not using an experimental design or for not integrating ethnomathematics and augmented reality simultaneously. Furthermore, 37 articles were assessed for eligibility through full-text review, and 16 were excluded for incomplete reporting or the absence of sufficient statistical data. Ultimately, 21 studies met all inclusion criteria and were included in the meta-analysis, as summarized in the PRISMA flowchart in Figure 1, reflecting the thoroughness of the selection procedure and the validity of the method.

4. Data Extraction

Relevant information from each study meeting the inclusion criteria was systematically compiled into a structured coding form. Data collected included author identity, year of publication, study location, number of participants, educational level, study design, digital innovations used, and effect size values or available raw quantitative data. The data collection process was conducted independently by two coders to minimize the potential for subjective bias. Any discrepancies in coding results were discussed collectively until a consensus was reached to ensure data accuracy and consistency.

To assess inter-coder reliability, five of the twenty-one primary studies were randomly selected and recoded by both coders. The level of agreement achieved was then analyzed using Cohen's Kappa coefficient, as formulated in Equation (1). The use of this reliability measure aims to ensure that the data extraction process is consistent and replicable. Thus, the internal validity of the meta-analytic data synthesis can be methodologically maintained (McHugh, 2012).

$$k = \frac{Pr(a) - Pr(e)}{Pr(e)} \quad (1)$$

Based on Equation (1), Pr(a) represents the level of empirical agreement actually observed between coders, while Pr(e) indicates the level of agreement that arises solely due to chance. Referring to the interpretation guidelines proposed by McHugh (2012), a concordance index value of or above 0.85 is interpreted as a very high agreement category. The calculation of the Kappa coefficient in this study produced a k value of 0.97, which indicates a very strong level of consistency between the two raters. This finding indicates that the coding procedures and instruments used have adequate levels of reliability and validity to support meta-analytic analysis.

5. Data Analysis

The quantitative analysis in this study was conducted using Comprehensive Meta-Analysis (CMA) software version 3 to calculate the effect size in the form of a standardized mean difference in the form of the Hedges' g index for each analyzed study. The random effects model approach was chosen to accommodate the variation between studies that is expected to arise due to differences in educational level characteristics, and the form of digital innovation carried out with the AR and AR-Geogebra categories. Interpretation of the magnitude of the effect size refers to the criteria proposed by Cohen et al. (2018), where a value of less than 0.20 is classified as an insignificant effect, a range of 0.20–0.49 as a small effect, 0.50–0.79 as a moderate effect, 0.80–1.29 as a large effect, and a value above 1.30 as a very large effect. The level of statistical heterogeneity between studies was evaluated using the Cochran's Q test to assess the consistency of the effects obtained. In addition, the possibility of publication bias was examined through asymmetry analysis on the funnel plot and testing using Egger regression.

C. RESULT AND DISCUSSION

1. Results

Twenty-one empirical studies were found to meet the inclusion criteria established in this study. The number of participants in each study varied, with sample sizes ranging from 17 to 188 participants, spanning elementary school, middle school, high school, and university levels. Details of the characteristics and a list of the studies analyzed are presented systematically in Table 1.

Table 1. Studies included in the analysis

Author, year	Education Level	Digital Innovation
(Apricillia et al., 2024)	Primary school	AR-Geogebra
(Arnoldus et al., 2025)	Primary school	AR-Geogebra
(Arifin & Efriani, 2025)	Junior high school	AR
(Cheong et al., 2024)	College	AR-Geogebra
(Dewi et al., 2024)	Junior high school	AR
(Gusteti et al., 2025)	College	AR-Geogebra
(Himayati et al., 2024)	Primary school	AR
(Iparraguirre-Villanueva et al., 2024)	Senior High School	AR-Geogebra
(Jampel & Antara, 2025)	Primary school	AR
(Mendez & Aviles, 2025)	Junior high school	AR-Geogebra
(Muwahiddah et al., 2021)	Junior high school	AR
(M. A. Nugroho et al., 2024)	Junior high school	AR
(Nurhasanah et al., 2023)	Primary school	AR
(Pasaribu et al., 2024)	Junior high school	AR
(Petrov & Atanasova, 2020)	Senior High School	AR-Geogebra
(Pramulia et al., 2025)	Primary school	AR
(Rahayu et al., 2025)	Junior high school	AR
(Richardo et al., 2023)	Junior high school	AR
(Ruslau et al., 2025)		AR-Geogebra
(Susanto et al., 2025)	Primary school	AR
(Siregar et al., 2025)	Primary school	AR

Based on Table 1, the 21 studies analyzed show a wide diversity of characteristics, both in terms of educational level and the type of digital innovation used. Distribution-wise, most studies were conducted at the elementary and junior high school levels, while the number of studies at the high school and university levels was relatively limited. In terms of digital innovation, there are two main categories: the use of Augmented Reality (AR) alone and AR combined with GeoGebra, with a tendency for AR–GeoGebra integration to be implemented more frequently at higher educational levels. This pattern indicates that technological complexity and the need for deeper conceptual exploration tend to increase with educational level. The diverse characteristics of these studies provide a strong basis for conducting moderator analyses to explain the variation in effect sizes found in the meta-analysis. Thus, this table confirms that the meta-analysis results represent a broad and relevant spectrum of learning contexts across educational levels. The findings of the overall analysis conducted with the CMA software are illustrated through a forest plot, which is displayed in Figure 2.

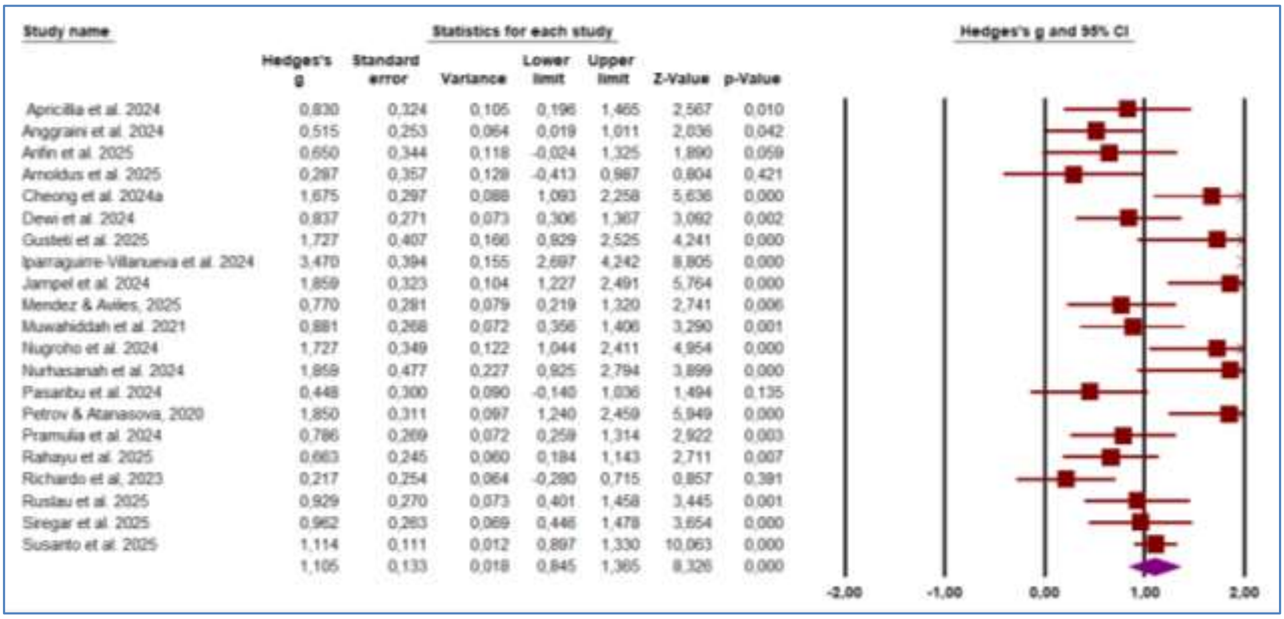

Figure 2. Meta-Analysis Forest Plot

Based on the meta-analysis forest plot of 21 studies as presented in Figure 2, it can be seen that almost all individual effect sizes (Hedges's g) are in the positive direction, with most of the 95% confidence intervals not crossing zero, indicating a significant and consistent effect of the interventions studied. The combined Hedges's g value is around g ≈ 1.105 with a 95% confidence interval of approximately 0.85 to 1.37, which is included in the large effect category, as well as a high Z value and p-value < 0.001, making it statistically highly significant. Although there are variations in effect sizes between studies ranging from small to very large effects, the relatively uniform direction of the effects indicates that these differences reflect variations in context, design, or sample characteristics, rather than differences in the direction of the effect. Thus, the results of this meta-analysis provide strong evidence that the interventions analyzed are substantially and consistently effective in improving students' mathematical performance. A summary of the results of the overall analysis of the studies is presented in Table 2 below.

Table 2. Results Summary of Data Analysis Results

Model	N	Hedges's g	Standard error	Test of null		Heterogeneity	
				Z-value	P-value	Q	P
Fixed-effects	21	1.03	0.05	18.12	0.00	96.14	0.00
Random-effects	21	1.10	0.01	8.23	0.00		

Based on Table 2, both the fixed-effects and random-effects models indicate that the analyzed interventions had a positive, strong, and statistically significant effect. In the fixed-effects model, a combined effect size of Hedges's g = 1.03 with a standard error of 0.05, a Z value of 18.12, and a p-value <0.001 was obtained, indicating a large and highly significant effect, assuming that all studies estimate the same true effect. Meanwhile, the random-effects model produced a slightly higher effect size, namely Hedges's g = 1.10 with a p-value <0.001, reflecting a more conservative and realistic estimate of the average effect because it takes into account the variation in effects between studies. The heterogeneity test showed a Q value of 96.14 with a p value of 0.000, indicating significant heterogeneity among the 21 analyzed studies. This finding indicates that differences in effect sizes are not solely caused by sampling error, but also by variations in study characteristics such as educational level, research design, cultural context, or type of intervention. Therefore, the presence of this significant heterogeneity methodologically justifies the use of a random-effects model and provides a strong basis for further analysis, including moderator analysis, to identify factors contributing to variation in effect sizes across studies and deepen understanding of the conditions under which interventions operate optimally. Further examination of the funnel plot was performed to ensure that the combined effect size was robust to publication bias. Figure 3 presents the funnel plot of the study.

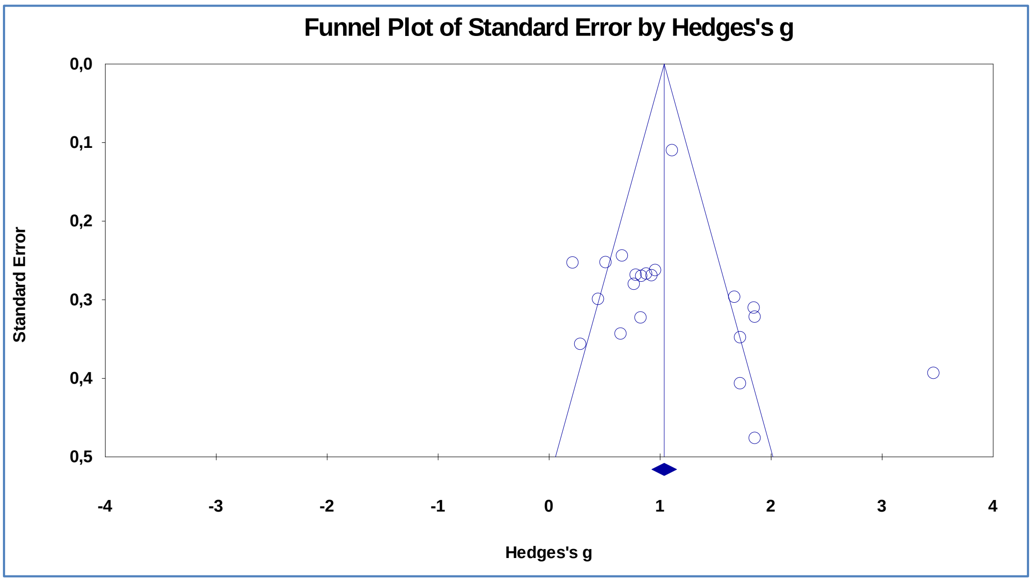

Figure 3. Research Funnel Plot

Based on the funnel plot between the standard error and Hedges's g, the distribution of study points generally forms a relatively symmetrical pattern around the pooled effect size (g ≈ 1.0–1.1), particularly in studies with smaller standard errors (the upper part of the plot), indicating high precision and consistency of the results. However, the lower part of the plot, representing studies with smaller sample sizes and larger standard errors, shows a somewhat skewed distribution, with several points tending to be on the right side of the funnel and one study with a very large effect size outside the main area. This pattern indicates the possibility of small-study effects or a tendency towards mild publication bias, although it does not show extreme asymmetry. Overall, this funnel plot suggests that publication bias does not appear to be dominant and the meta-analysis results are relatively stable. However, these findings still need to be confirmed through formal statistical tests (e.g., Egger's test or trim-and-fill) to more objectively determine the extent and implications of publication bias. This study considered educational level and the type of digital innovation used as moderators. Since the heterogeneity test was accepted, it was necessary to proceed with an examination of moderator variables that might be related to the overall combined effect size of the study. Table 3 shows the results of the moderator analysis.

Table 3. Results of the study moderator analysis

Moderator Variables	Category	N	Hedge's g	Heterogeneity (Qb)	df(Q)	P
Educational level	Primary school	8	1.19	16.81	3	0.001
	Junior high school	9	0.89			
	Senior high school	2	1.28			
	Colledge	2	1.63			
Digital innovation	AR	12	0.93	8.46	1	0.004
	AR-Geogebra	9	1.30			

Based on Table 3, the results of the moderator analysis based on education level indicate that this variable plays a significant role in explaining the variation in effect sizes between studies, as indicated by the significant between-group heterogeneity (Qb = 16.81; p = 0.001). Descriptively, the strongest intervention effect was found at the tertiary level (Hedges' g = 1.63), followed by high school/equivalent (g = 1.28) and elementary school (g = 1.19), while a relatively lower effect was observed at junior high school (g = 0.89). This pattern indicates that intervention effectiveness tends to increase with educational level, possibly related to students' cognitive readiness, abstraction skills, and more mature prior learning experiences at higher levels. Thus, education level proved to be a significant moderator in influencing the magnitude of the intervention impact analyzed.

Furthermore, the moderator analysis based on the type of digital innovation also showed a significant difference in effect sizes between categories (Qb = 8.46; p = 0.004). Studies using Augmented Reality (AR) combined with GeoGebra yielded larger effect sizes (Hedges's g = 1.30) compared to using AR alone (g = 0.93). These findings suggest that integrating AR with dynamic mathematics software like GeoGebra can enrich visual representations, increase interactivity, and deepen students' conceptual understanding, thus having a stronger impact on learning outcomes. Overall, these results confirm that variations in effectiveness across studies are influenced not only by learner characteristics (educational level), but also by the complexity and level of integration of the digital innovations used, reinforcing the importance of contextualized and integrated intervention design.

2. Discussion

The overall analysis results indicate that the interventions analyzed have a positive, strong, and significant impact on learning outcomes, with a combined effect size in the large category. The consistent, predominantly positive direction of the effect across most studies indicates that digital technology-based approaches, particularly those integrating cultural context, can improve students' conceptual understanding, engagement, and motivation in mathematical learning. Furthermore, significant heterogeneity suggests that the intervention's effectiveness is not uniform across contexts. This variation reflects differences in student characteristics, educational level, learning design, and the type of digital innovation used. Therefore, the use of a random-effects model is appropriate because it provides a more realistic estimate of the effect. Theoretically, these findings reinforce the view that immersive technology-based learning, such as Augmented Reality (AR), can bridge abstract concepts with more concrete learning experiences (Mendez & Aviles, 2025; Pangestu et al., 2024; Tamur et al., 2024, 2026; Tamur, Ngao, et al., 2025; Yilmaz & Batdi, 2021). Thus, the results of this meta-analysis provide a strong empirical basis for the development of innovative, contextual and meaningful learning.

Furthermore, moderator analysis showed that educational level significantly influenced the magnitude of the intervention's impact. The greater effect at higher education levels indicates that students with more mature cognitive abilities and learning experiences tend to utilize AR-based technology more optimally. At the college and high school levels, students are able to integrate visual, symbolic, and conceptual representations more effectively (Cheong et al., 2024; Gusteti et al., 2025; Mendez & Aviles, 2025). Meanwhile, at the elementary and junior high school levels, although the effect remains positive and significant, the level of material complexity and limited abstraction abilities can limit the full exploration of the technology's potential. These findings align with cognitive development theory, which emphasizes mental readiness as a prerequisite for utilizing advanced learning technology (Pakpahan & Saragih, 2022). Therefore, AR implementation needs to be tailored to the developmental characteristics of students at each level. These adjustments include content simplification, adequate scaffolding, and a contextualized pedagogical approach.

Furthermore, a moderator analysis of digital innovation types revealed that the integration of AR with AR-GeoGebra had a greater impact than using AR alone. This suggests that the main strength of digital learning lies not only in the immersive visualization of AR, but also in the support of exploratory and dynamic tools such as GeoGebra (Arnoldus et al., 2025; Arymbekov et al., 2023; Cheong et al., 2024; Iparraguirre-Villanueva et al., 2024; Petrov & Atanasova, 2020; Tamur et al., 2026). The combination of the two allows learners to not only observe virtual objects but also to interactively manipulate, explore, and verify mathematical concepts. In this context, AR acts as a bridge connecting modern technology with cultural and contextual learning experiences, while GeoGebra strengthens mathematical understanding through dynamic and accurate representations. This synergy creates a rich and meaningful learning ecosystem. These findings emphasize the importance of integrated, rather than partial, learning design. Therefore, the development of future learning media needs to prioritize collaboration across digital platforms.

However, this study has several limitations that require consideration. First, the number of studies in several moderator categories, particularly at the high school and university levels, is relatively limited, so generalization of the results requires caution. Second, variations in research design and measurement instruments across studies have the potential to influence the consistency of effect sizes. Third, although indications of publication bias are relatively low, their presence cannot be completely ruled out. Therefore, future research is recommended to involve a larger and more balanced number of studies in each moderator category. Future research should also explore other moderators, such as cultural context, intervention duration, and teacher competency in implementing the technology. Furthermore, long-term experimental studies are essential to assess the sustainability of the impact of AR-based learning. Thus, future research is expected to further strengthen AR's role as a bridge between technology, culture, and meaningful learning, optimally supported by GeoGebra.

D. CONCLUSION AND SUGGESTIONS

Overall, this meta-analysis provides strong empirical evidence that Augmented Reality (AR)-based learning, particularly when integrated with cultural contexts and supported by dynamic software such as GeoGebra, has a significant and substantial impact on improving mathematics learning outcomes across a wide range of educational settings. The large aggregated effect size confirms AR's role as an effective pedagogical bridge between digital technologies and cultural heritage, strengthening conceptual understanding through immersive visualization and interactive mathematical exploration. The primary theoretical contribution of this meta-analysis lies in establishing an integrated conceptual framework that empirically connects culturally responsive pedagogy, digital innovation, and immersive technology within mathematics learning. By quantitatively synthesizing evidence at the intersection of AR and ethnomathematics, this study advances theoretical discourse beyond isolated examinations of technology integration or cultural context, demonstrating that their synergistic interaction produces a robust learning effect. In doing so, it provides a clearer explanatory basis for understanding how digital immersion can mediate cultural meaning-making in mathematical cognition.

However, significant heterogeneity across studies suggests that the effectiveness of AR-supported interventions is context-dependent rather than universal. Variations in educational level, depth of technological integration, and instructional design features appear to moderate the magnitude of learning gains. The limited number of studies in certain subcategories, diversity in research designs, and potential publication bias indicate the need for further empirical refinement. Future research should therefore investigate additional moderating variables, employ more rigorous and longitudinal experimental designs, and expand implementation of AR–GeoGebra approaches across more diverse cultural contexts. Such efforts will not only deepen theoretical understanding but also generate more precise and sustainable guidance for meaningful technology-based mathematics learning..

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