International Journal of Science and Mathematics Education
https://doi.org/10.1007/s10763-025-10546-x

Augmented Reality for Mathematics Achievement: A Meta-Analysis of Main and Moderator Effects

Eunhye Flavin[1] · **Sunghwan Hwang**[2] · **Matthew T. Flavin**[3]

Received: 24 October 2023 / Accepted: 3 January 2025

Abstract

Augmented reality (AR) continues to demonstrate its impact on education. Despite the increasing interest in AR as a pedagogical tool and the evidence gathered from literature reviews, there has been limited information on how AR may improve the mathematics achievement of K-12 students. This study aims to synthesize the effects of AR use on the mathematics achievement of K-12 students. In this study, we conducted a meta-analysis of 22 experimental studies with 25 different samples published before July 2023. The findings revealed a medium effect size of AR use on the mathematics achievement of K-12 students ($g=0.765$), indicating its positive influence. We further conducted moderator analysis to investigate variations in this impact, considering three research characteristics variables (mathematics domain, educational level, and treatment duration), and two AR features variables (connectivity and integration of virtual objects). The results of the moderator analysis showed that the integration of virtual objects variable had a significant moderating effect, implying the effect of AR on the mathematics achievement of K-12 students may vary depending on the integration of virtual objects. However, the effects of other moderating variables were not significant. We provided further implications for future research and practice.

Keywords Augmented reality · K-12 students · Mathematics achievement · Meta-analysis · Mathematics education

Introduction

Driven by the rapid expansion of mobile technology and its growing suite of advanced sensors, augmented reality (AR) has increasingly emerged as an accessible technology for consumers (Rejeb et al., 2023). Researchers estimated that there are 1.7 billion active mobile AR user devices in 2024, which constitutes approximately

Eunhye Flavin and Sunghwan Hwang are contributed equally to this work.

Extended author information available on the last page of the article

Published online: 29 January 2025

21% of the world population (Statista, 2024). Distinguished from virtual reality (VR) by its incorporation of virtual objects into the physical surroundings of the user through a camera feed (Ibáñez & Delgado-Kloos, 2018), AR is shifting how people explore, play, and communicate across their daily lives. It is also influencing the workflows of various industries, including gaming, finance, and medical services (Parekh et al., 2020).

In particular, there is a growing interest among educators to utilize AR as a pedagogical tool (Cai et al., 2022; Chang et al., 2022; Li et al., 2021; Wang et al., 2025), for which it shows promise for helping students connect abstract and complicated concepts to concrete and real-world contexts and enhance their learning outcomes (Chen, 2019; Estapa & Nadolny, 2015). Linked to improving the quality of education, industry, and daily life, AR may even be key to addressing the sustainable development of our society (Abad-Segura et al., 2020). This potential has led many governments, institutions, and private companies to adopt AR as an educational tool.

Accompanying the growth of AR and its application to education, previous literature reviews have documented the rapid progress in various subject domains. Some researchers have examined research trends of AR within the broader scope of education (e.g., López-Belmonte et al., 2023). Others have focused on a certain subject domain, such as language education (Majid & Salam, 2021), STEM education (Sırakaya & Sırakaya, 2022), and mathematics education (Korkmaz & Morali, 2022). These reviews descriptively summarized previous studies, focusing on their research topics, technologies used, sample sizes, and publication years.

Some scholars have conducted a meta-analysis to quantitatively appraise and synthesize the effects of AR on student achievement (e.g., Chang et al., 2022; Li et al., 2021; Özdemir et al., 2018). However, these meta-analyses did not focus the role of AR use on mathematics, particularly for mathematics achievement. Mathematics is an important topic where it serves as a "gatekeeper course (Moses & Cobb, 2001, p. vii)," and mathematics achievement can affect student success in school, entrance into college, and success in career (Skovsmose, 2019). Mathematics also serves as the cornerstone for comprehending other subjects and proves invaluable in understanding the complex structure of contemporary society (Kavaz & Kocak, 2024; Maass et al., 2022). Therefore, our focus attends to the role of AR use on such an important topic. In sum, our study aims to add nuance to the relationship between AR use and the mathematics achievement of K-12 students by investigating the roles of main and moderating variables (details will be discussed later). By providing empirical evidence through a meta-analysis, our work will inform practical implications and guidance on how AR can be utilized for mathematics learning and teaching for K-12 students.

Literature Review

The Characteristics of AR

Azuma (1997) defines AR as a "system that has the three characteristics: (1) the combination of real and virtual objects, (2) real-time interactivity, and (3) registration in three dimensions (3D)" (p. 356). To convey the qualities of their physical surroundings, the AR system needs a set of appropriate sensors, which typically includes a camera. For more advanced applications, the system may also incorporate 3D scanning and inertial measurements. The 3D visualization allows students to engage with 3D synthetic objects as a means of enhancing their visual understanding of the learning material (Abdul Hanid et al., 2022; Baltacı & Çetin, 2022; Demitriadou et al., 2020; Ibáñez et al., 2020; Koparan et al., 2023; Lin et al., 2015). As an example, Demitriadou et al. (2020) demonstrate how students can use a tablet-based system to scan the image of a rectangle from a printed worksheet, which superimposes a 3D rectangular prism on the screen (Demitriadou et al., 2020). Thus, this capability aids students in identifying and analyzing 3D objects (Koparan et al., 2023).

The AR system must also incorporate software that renders virtual objects, often supported by an application programming interface provided by the manufacturer. Finally, the system requires a display, which typically takes the form of a visual monitor (Billinghurst et al., 2015). An example of such an AR system would be one that tracks the trajectory of a virtual object in the image plane as it moves around a scene, modifies it with virtual features, and displays it in real-time on a video display (Brito & Stoyanova, 2018).

AR resembles VR in many respects, with the exception that VR does not incorporate the surroundings of the user. VR might use sensors that track the motion of the user, but it ignores input from the physical environment. While VR shuts down real-view and operates in the virtual environment, AR supplements real-view with virtual information.

In the context of education, AR systems can be categorized based on two distinct affordances: connectivity and integration of virtual objects. First, connectivity pertains to the ability of the user to utilize internet and location-based input as part of the AR system. AR features are experienced through handheld devices, such as mobile phones or tablets, which are equipped with wireless connectivity and location-based technology (Abdul Hanid et al., 2022; Ibáñez & Delgado-Kloos, 2018). This feature, implemented typically in mobile devices, enables situated and ubiquitous learning, extending beyond the confines of desktop computers within a specific classroom setting. With the aid of location-aware mobile devices, users can seamlessly access context-sensitive virtual information. Some AR apps may rely on trigger image markers like QR codes to activate virtual content. However, more recently, GPS-based AR apps have eliminated the need for image markers, allowing users to overlay location-specific information onto existing spaces (Wu et al., 2013).

The second affordance of AR is its ability to display invisible mathematics concepts or unobservable events through virtual objects (Abdul Hanid et al., 2022; Aldalalah et al., 2019; Baltacı & Çetin, 2022; Cai et al., 2020; Wu et al., 2013). Cai et al. (2020) provided an illustration of this capability, what we referred to as 'integration of virtual objects.' In their study, students used AR software to record the results of coin tosses for the calculation of probability. The AR software then automatically generated a virtual object in the form of a curve graph, which was augmented using the recorded coin toss outcomes. This tool simplifies the steps needed for the students to visualize an outcome, removing the cognitive burden and latency of manual graphing. Ultimately, as reported by Wu et al. (2013), this real-time visualization improved understanding of abstract and invisible concepts by the students. del Cerro Velázquez and Morales Méndez (2021) also claimed such virtual objects can help students understand mathematical concepts and gather knowledge with greater ease.

Finally, advanced AR technologies have the ability to spatiotemporally integrate virtual objects into the physical surroundings of the user (e.g., Cai et al., 2020). In contrast with marker-based approaches (e.g., Arvanitaki & Zaranis, 2020; Estapa & Nadolny, 2015), these integrated systems employ scene reconstruction and tracking to maintain intuitive physical relationships. In the previous work of Flavin and Flavin (in press), for example, students wielded an AR smartphone app that helped them measure the volume of physical objects by anchoring virtual boxes of known volume onto their absolute position.

AR use in Mathematics Education

With the emergence of the reform movement, mathematics educators have criticized traditional mathematics instructional practices, such as rote memorization, test-oriented instruction, and direct instruction by teachers in a manner that ignores how students construct that knowledge (Bray & Tangney, 2017). This movement encourages teachers to grant students access to technologies that enable them to exercise agency in their investigation of mathematics. These learning environments foster mathematical activities such as sense-making, exploration, communication, reasoning, justification, problem-solving, and communication (National Council of Teachers of Mathematics [NCTM], 2000, 2011).

Although its use in the mathematics classroom is still in its early stages, AR has been positioned as a beneficial tool (Estapa & Nadolny, 2015; Wang et al., 2025). Flores-Bascuñana et al. (2019) examined how elementary students understand 3D geometric solids and their characteristics. They found that students who engaged in AR-based activities achieved significantly higher scores compared to those who learned mathematics through conventional teaching methods. Similar findings have been observed across various educational levels, such as preschool (Gecu-Parmaksiz & Delialioglu, 2019), secondary school (Abdul Hanid et al., 2022), and college (Medina Herrera et al., 2019).

These positive outcomes can be attributed to the affordances and mediating roles of AR in mathematics teaching and learning. According to Bujak et al., (2013), what sets AR apart from other traditional mathematics instruction is its unique physical, cognitive, and contextual characteristics. In terms of a physical attributes, AR affords students the ability to interact with mathematical objects as embodied representations with spatiotemporal alignment. By coupling graphical representations (e.g., real objects) with mathematical notations (e.g., virtual symbols, letters, and signs), AR delivers abstract mathematics concept in a real-world setting. This feature helps students to make a symbolic link between mathematics concepts and concrete models, thereby reducing working memory load (Cetintav & Yilmaz, 2023). Also, teachers can leverage such characteristic of AR in explaining how mathematical notations are connected to the physical surroundings of the users (Flavin & Flavin, in press). Finally, in terms of the contextual characteristic, AR has the capacity to create a student-centered learning environment. Within this environment, teachers could allow students to cultivate their own knowledge and skills through collaboration, examination, contextual relevance, and personal relevance (Hidajat, 2024; Lin et al., 2013). Despite the growing body of research in this field, limited studies have synthesized the effects of AR on the mathematics achievement of K–12 students.

Review of Previous Meta-analysis Studies

Several researchers have conducted meta-analyses to examine the impact of AR on education and reported a significant effect size on the relationship (e.g., Chang et al., 2022; Özdemir et al., 2018; Tekedere & Göke, 2016). They also examined various moderating variables in their analysis, which helps to identify the conditions under which the relationship between AR use and student achievement is strengthened or weakened.

Chang et al. (2022) analyzed 134 articles encompassing various educational levels from preschool education to adult training. Their analysis, comparing AR with non-AR instruction, with a random effects model (REM), found significant effects of AR on cognitive ($g=0.65$), affective ($g=0.49$), behavioral ($g=0.74$) learning outcomes. They further reported that within the cognitive domain (knowledge and skill), most studies demonstrated a positive correlation between treatment duration and effect size. However, moderating effects related to education levels (elementary, secondary, postsecondary, and others) were found insignificant.

Similarly, Özdemir et al. (2018) examined 16 studies spanning elementary to undergraduate students and found a medium effect size ($g=0.517$) regarding the influence of AR on student academic achievement. The moderating effect of educational level was insignificant, aligning with Chang et al.'s (2022) study. Furthermore, Tekedere and Göke (2016) examined 15 studies and found a medium effect size ($g=0.677$) regarding the effects of AR in education.

Compared to previous studies that analyzed the effects of AR across all educational levels, Kalemkuş and Kalemkuş (2023) analyzed the impact of AR on science achievement of K–12 students with 16 studies and found a medium effect size ($g=0.643$). Similarly, Li et al. (2021) examined AR's impact on academic achievement of K–12 students with 40 samples and found a small effect size ($g=0.437$). Regarding moderating variables, the effects of treatment duration and subjects were significant. In particular, the longer durations yield larger effect sizes. However, the moderating effect of educational level was not significant, suggesting that the relationship between AR and student achievement was not influenced by educational levels. Li et al. further found a small effect ($g=0.407$) in their study on the impact of AR use on mathematics achievement using 9 samples.

The Current Study

This study embarked on a meta-analysis to investigate the effects of AR on mathematic achievement of K-12 students. We also included moderating variables in our analysis to provide a more nuanced picture of the conditions under which the effects of AR on mathematics achievement in K-12 students are strengthened or weakened. To conduct these analyses, we developed an analytical framework (see Fig. 1) and selected moderating variables drawing from previous studies (e.g., Baltacı & Çetin, 2022; Cai et al., 2022; Chang et al., 2022; Li et al., 2021; Özdemir et al., 2018; Wu et al., 2013). The moderating variables for this study consisted of research characteristics variables (mathematics domain, treatment duration, and educational level) and AR feature variables (connectivity and integration of virtual objects). Further details regarding these moderating variables are provided in the Methods section. The present study aimed to address two research questions as follows: RQ1. What about the overall effects of AR use in mathematics achievement of K–12 students?; RQ2. What moderating variables significantly influence the relationship between AR use and mathematics achievement of K–12 students?

Methods

Article Selection Process

A set of selection criteria was utilized to retrieve relevant articles as of July 2023, and Fig. 2 illustrates the data selection process. First, we collected articles that include terms related to AR, mathematics (e.g., algebra), and K-12 education (e.g., elementary school) within their titles or abstracts (see Table 1). We used four research databases to compile relevant articles: ERIC, SCOPUS, Web of Science, and ProQuest Dissertation & Theses Global, resulting in the acquisition of 2,178 articles. Second, we excluded non-English-written articles, yielding a total of 1,729 English-written articles. Third, the data collected was imported into EndNote 20 to eliminate duplicate entries, thereby leaving 1,142 articles.

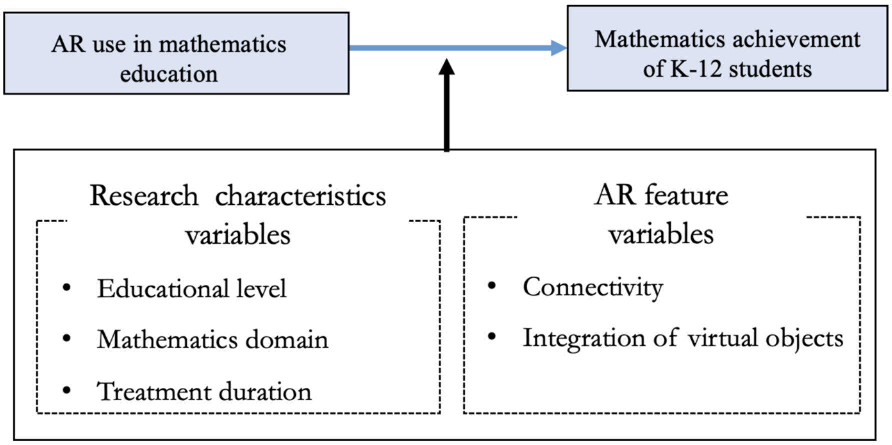


Fig. 1 Analytical framework

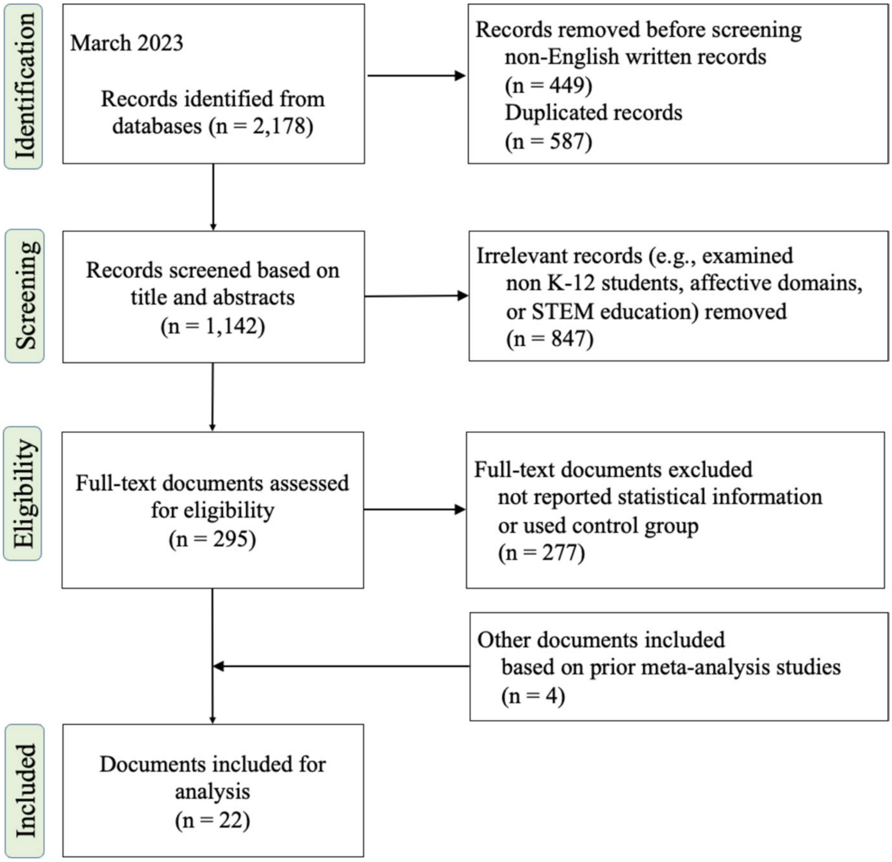


Fig. 2 The Prisma follow diagram of this study (Moher et al., 2009)

Table 1 Search string used for retrieving relevant articles

AR-related terms	Mathematics-related terms	K-12 education-related terms
"augmented reality" "augmenting reality" "ar"	"mathematics" "geometry" "number" "operation" "algebra" "measurement" "ratios" "rates" "probability" "statistics"	"preschool" "kindergarten" "elementary school" "primary school" "middle school" "high school" "secondary" "students" "children"

Fourth, we reviewed the titles and abstracts of each article to determine their relevance to AR in K-12 mathematics education. Those articles deemed irrelevant (e.g., those focusing on college students, affective domains, or STEM education) were removed, resulting in a pool of 295 articles. Fifth, we examined the full-texts of the remaining articles. We excluded those that lacked sufficient statistical information (e.g., mean, standard deviation, and sample size) required for effect size calculations. We specifically selected articles with a quasi-experimental design (examining control and experimental groups) for enhanced internal validity, allowing for a more rigorous investigation of the effects of AR (Chang et al., 2022). We attained 18 articles through this process. Sixth, we reviewed the references of prior meta-analysis studies (e.g., Li et al., 2021) and found four additional studies that examined the relationship between AR and mathematics achievement of K–12 students. This selection process resulted in a final compilation of 22 articles, consisting of 25 distinct analysis samples.

Coding Process

According to the analytical framework, we coded individual studies across five moderating variables. Table 2 shows the final coding scheme utilized in this study. To assign a code to research characteristics variables, we used an inductive content analysis approach (Elo & Kyngäs, 2008). The authors initially created draft codes through an open coding process and refined them through subsequent revision and discussion. For example, regarding mathematics domains, we coded our data into two domains: number and algebra (NA) and geometry and measurement (GM), since the other mathematics domains were not represented. Moreover, given that most articles implemented AR intervention of less than 10 h (Cai et al., 2020) or more than 10 h (e.g., Yousef, 2021), the data was classified into short (less than 10 h) or long (equal to or more than 10 h) based on Li et al. (2021). For connectivity, we used two codes: 'strong' and 'weak'. 'Strong' refers to studies that do not need a trigger image (e.g., QR code), while 'weak' refers to studies that require a trigger image. Regarding the integration of virtual objects in the AR feature variables, the authors independently assigned codes to the collected articles based on the presence of each feature (category: yes or no). For example, if a study used an AR device that integrating virtual objects (e.g., Abdul Hanid et al., 2022), we coded it as 'yes' for the variable of integration of virtual objects. Any discrepancies were resolved through discussion.

Data Analysis

As a complementary approach to qualitative literature review, meta-analysis has obtained growing popularity within academic journals and research institutions. This method draws overarching conclusions by compounding research findings from previous studies and analyzing them using quantitative analysis techniques (Hedges & Olkin, 2014). Based on the prior studies (Borenstein et al., 2009; Chang et al., 2022; Kalemkuş & Kalemkuş, 2023), we examined heterogeneity, overall effect size, publication bias, and the effects of moderating variables (i.e., subgroup analysis), using a comprehensive meta-analysis (CMA) 3.0 program.

Table 2 Coding schemes

Moderating variables		Coding scheme
Research characteristics variables	Educational level	primary school, middle school, high school
	Mathematics domain	number and algebra (NA), geometry and measurement (GM)
	Treatment duration	short (less than 10 h) long (equal to or more than 10 h)
AR features variables	Connectivity	strong (does not need a trigger image), weak (needs a trigger image)
	Integration of virtual objects	yes (displays invisible mathematics concepts and/or unobservable events through virtual objects) no (does not display invisible mathematics concepts and/or unobservable events through virtual objects)

First, we assessed the heterogeneity of the collected articles using Q statistics and I^2. Q statistics inspects whether the collected studies share a common effect size (Hillmayr et al., 2020). The significant Q statistics indicates heterogeneity across studies, meaning that the observed differences in the collected studies "exceed the level expected as a result of the sampling error (Linden & Hönekopp, 2021, p. 358)." I^2 examines "the ratio of true heterogeneity to total variation in observed effects" (Borenstein et al., 2009, p. 120). I^2 values greater than 25%, 50%, and 75% could be interpreted low, medium, and large heterogeneity of the collected data (Higgins et al., 2003). Therefore, if significant Q statistics and greater than 50% of I^2 values are observed (Borenstein et al., 2009), it indicates that due to the variations in the collected studies, it is prudent to use REM and assess which moderator variable influences the intervention effect in a way that varies across subgroups.

Second, we estimated the overall effect sizes based on the effect size of each study. When studies did not report effect sizes, we calculated them using mean, standard deviation, and sample size. Furthermore, we opted for Hedges' g over Cohen's d. Because Hedges' g "take[s] into account the studies' sample sizes to reduce bias" (Chang et al., 2022, p. 6), it is more appropriate choice for calculating effect sizes for small samples compared to Cohen's d, which is our study's case. While Hedges' g is the modified formula of Cohen's d, the interpretation of the effect size is the same (Chang et al., 2022). They use the same thresholds (Cohen, 1988) to categorize effect sizes as small (between 0.2 and 0.49), medium (between 0.5 and 0.79), and large (over 0.8). We also followed Bernard et al.'s (2004) suggestions for effect size computation. For example, when a longitudinal study reported multiple achievement scores (e.g., first, second, and third scores, Gargrish et al., 2021), we used the final scores to calculate effect sizes. Similarly, if a study reported several achievement scores within the same mathematics domain (e.g., visualization and computation thinking scores of a geometry, Abdul Hanid et al., 2022), we computed a single effect size per study using CMA (Chang et al., 2022). However, when a study reported mathematics achievement for completely different groups (e.g., high and low performing groups, Lin et al., 2015), a separate meta-analysis was conducted.

Third, we assessed the publication bias using funnel-plot, trim-and-fill method, classic fail-safe N test and Orwin's fail-safe N test (Borenstein et al., 2009). An asymmetrical distribution in a funnel-plot indicates publication bias in the collected data. In this case, the differences between observed and adjusted effect sizes were compared using the trim-and-fill method. The fail-safe N tests evaluate the number of studies needed to nullify the findings of the study based on the p-value (Borenstein et al., 2009). We adopted a significance level of 0.05 for the current tests (Cheung & Slavin, 2013).

Lastly, using a Q_B test, we conducted subgroup analyses to examine the influence of moderating variables (Borenstein et al., 2009). Similar to ANOVA tests, a significant Q_B represents heterogeneity across different groups, which could be interpreted that the relationship between AR use and mathematics achievement of K-12 students were influenced by the moderating variables. Conversely, a non-significant Q_B indicates insignificant differences across groups.

Results

Heterogeneity and Overall Effect Size

The heterogeneity analysis revealed a significant difference in effect sizes ($Q=69.543$; $df=24$; $p<0.001$). The I^2 analysis also showed the medium heterogeneity ($I^2 = 65.489$). Given that the current study examined the effects of AR across various populations of K-12 students and considering the heterogeneity among the studies, this study adopted REM to evaluate the effect size of the collected data (Borenstein et al., 2009). These results could also be interpreted that the variance between effect sizes was partially influenced by moderating variables, implying the need for subgroup analysis (Borenstein et al., 2009).

Under the REM, the overall effect size of AR use on mathematics achievement of K-12 students was 0.765 ($SE=0.100$, $k=25$, 95% CI: 0.569–0.961, $Z=7.643$, $p<0.001$). This finding indicates that, regarding mathematics achievement, the standard deviation of AR use group was 0.765, which is higher than non-AR use group.

As shown in Table 3, all studies exhibited a positive effect, ranging from 0.047 (Lin et al., 2015) to 2.118 (Gargrish et al., 2022). Lin et al.'s (2015) study, with the smallest effect size, examined the influence of the use of webcam-based AR device on the geometry learning of Taiwan high school students (Lin et al., 2015). Gargrish et al. (2022) presented the largest effect size due to a wide gap in the test scores between the pre-test and post-test (the control group's test scores decreased, while the experimental group's test scores increased). This study analyzed the effect of mobile or tablet-based AR device implementation on geometry learning among high students in India.

To examine the existence of outliers with large effect sizes that might skew the overall effect size (Cheung & Slavin, 2013), we implemented a "sensitivity analysis" (Borenstein et al., 2009, p. 393) in CMA by excluding one study (or sample) at a time. For example, to analyze the influence of Gargrish et al. (2022) on the overall effect size, which has the largest effect size ($g=2.118$), we removed this study from the dataset and examined the changes in the overall effect size without the study. The results of the sensitivity analysis show that the modified overall effect size without a study falls between 0.715 and 0.795 (within the 95% confidence interval of the original effect size of 0.765, which is 0.569–0.961). Thus, we concluded that while the effect sizes of some studies are relatively large, the overall effect size was not significantly influenced by them. In other words, skewness in our dataset is negligible.

Publication Bias

We attempted to detect publication bias using a funnel plot. In Fig. 3, each of the collected articles (samples) is represented as an open circle. The middle bar represents the observed mean effect size of the collected articles. Open circles on the left or right side of the middle bar indicate that their effect sizes are less or larger

Table 3 The descriptive information of individual studies

Study name	N	Hedges's g	SE	Education level	Math domain	Duration (hours)	Connectivity	Integration of virtual objects
Abdul Hanid et al. (2022)	124	1.140	0.196	Middle	GM	-	Yes	Yes
Aldalalah et al. (2019)	86	0.856	0.225	Middle	GM	-	-	-
Angraini et al. (2023)	30	1.145	0.394	Middle	GM	6	Yes	Yes
Arvanitaki and Zaranis (2020)	46	0.618	0.306	Primary	GM	6	Yes	No
Baltacı and Çetin (2022)	33	0.752	0.369	High	GM	16	Yes	Yes
Cai et al. (2020)	68	0.498	0.246	Middle	-	3	Yes	Yes
Cetintav and Yilmaz (2023)	40	0.769	0.328	Middle	GM	24	No	No
Chen (2019)_1	41	0.574	0.321	Primary	NA	1	Yes	Yes
Chen (2019)_2	41	0.884	0.329	Primary	GM	1	Yes	Yes
Cheng et al. (2018)	20	0.106	0.448	Middle	GM	-	-	-
del Cerro Velázquez and Morales Méndez (2021)	48	1.023	0.307	High	NA	12	Yes	Yes
del Cerro Velázquez and Morales Méndez (2021)	48	1.082	0.309	High	GM	12	Yes	Yes
Demitriadou et al. (2020)	20	0.884	0.470	Primary	GM	1	Yes	No
Drury-stotz (2018)	56	0.465	0.274	-	NA	2	Yes	No
Gargrish et al. (2022)	54	2.118	0.341	High	GM	-	No	Yes
Hwang et al. (2023)	50	0.603	0.289	Primary	GM	6	Yes	Yes
Ibili et al. (2020)	103	0.326	0.199	Middle	GM	-	Yes	Yes
Koparan et al. (2023)	98	1.646	0.234	Middle	GM	-	Yes	Yes
Ibáñez et al. (2020)	45	1.606	0.343	Middle	GM	1	Yes	No
Lin et al. (2015)_1	38	0.047	0.324	Middle	GM	1	No	No
Lin et al. (2015)_2	38	0.053	0.365	Middle	GM	1	No	No
Nadzri et al. (2023)	59	0.683	0.268	Primary	GM	-	No	No
Poçan et al. (2023)	73	0.702	0.241	Middle	NA	-	No	No

Table 3 (continued)

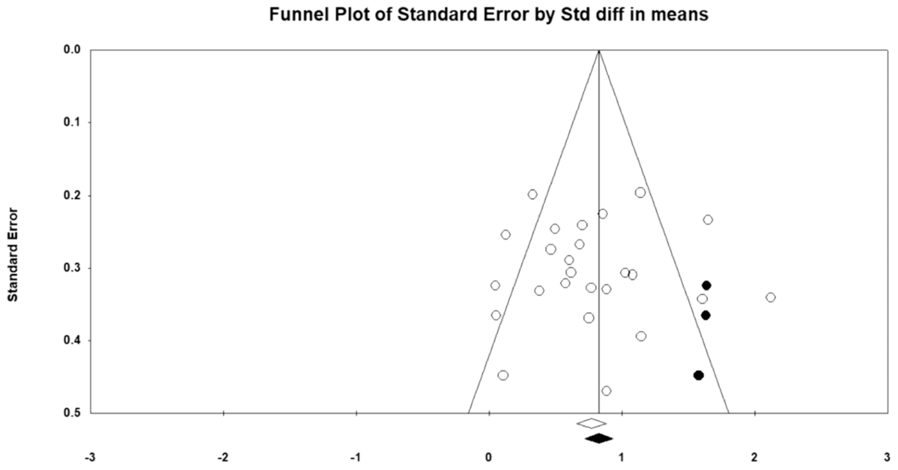
Study name	N	Hedges's g	SE	Education level	Math domain	Duration (hours)	Connectivity	Integration of virtual objects
Tsuei and Chiu (2021)	37	0.377	0.332	Primary	NA	-	No	No
Yousef (2021)	62	0.124	0.254	Primary	GM	48	Yes	No

SE standard error, *NA* number and algebra, *GM* geometry and measurement. Connectivity = whether a trigger image marker was used or not. The dash cell indicated that the study did not report accurate information than the observed mean effect size. The funnel plot analysis showed that while the individual sample (the open circle) had a symmetrical cluster near the mean effect size, the left side has more circles. This result implies that our dataset has more studies with as a small effect size than studies with a large effect size (Borenstein et al., 2009). Thus, we implemented the Trim and Fill method to examine the possible effect of publications bias.

The Trim and Fill method allows researchers to examine the influence of missing studies (in our case the studies with a larger effect size) on the observed mean effect size (Borenstein et al., 2009). As shown in Fig. 4, CMA automatically imputed three plausible missing studies on the right side to make a symmetrical distribution and recalculated the mean effect size. The observed mean effect size (g = 0.765) with the original 25 samples (the open diamond) and the adjusted mean effect size (g = 0.824) with the original 25 samples and three imputed samples (the filled diamond, adjusted mean effects by imputing plausible missing studies to become symmetric) were not same. However, the adjusted mean effect size falls within the 95% confidence interval (0.569 – 0.961) of the observed mean effect size. Thus, we conclude that publication bias is negligible as the observed mean effect size was not significantly influenced by potentially missing studies (Hillmayr et al., 2020).

We also conducted a classic fail-safe N test and Orwin's fail-safe N test to estimate the number of additional studies that are required to turn the effect size reported in this study to be insignificant (Erasmus Research Institute of Management, n.d.). At a significance level of 0.05, the result from a classic fail-safe N test was 1078 and Orwin's fail-safe N test was 359. This result means that according to the classic fail-safe N test, 1078 studies with zero effect size would be needed to nullify the findings of this study. Similarly, the result from Orwin's fail-safe N test means that 359 studies with 0.05 effect sizes "would be required to bring the mean effect size to a trivial level" (Cheung & Slavin, 2013, p. 100). In sum, due to a large volume of the studies needed to nullify the findings of this study, we conclude that

Fig. 3 The Funnel Plot analysis with 25 samples



Note. The black circles indicate the imputed samples, and the black diamond represents the adjusted mean effect size.

Fig. 4 The Funnel Plot analysis after trim-fill method with 25 samples and three imputed samples

observed mean effect size in this study is robust (Borenstein et al., 2009; Hillmayr et al. 2020).

Moderator Analysis

Research Characteristics Variables

Table 4 shows the results of the moderator analysis on research characteristics variables. Regarding mathematics domain, 19 samples examined geometry and measurement (GM) and five samples studied number and algebra (NA). The analysis of the moderating effects indicated that the effects of AR use on mathematics achievement did not significantly differ across mathematics domains (Q_B= 0.527, *df*=1, p=0.468). The use of AR produced a significant effect in number and algebra (g=0.631**) and geometry and measurement (g=0.818***), indicating that AR use for both mathematics domains positively influenced student achievement.

For the education level, more than half of the samples focused on secondary students (middle school=12, high school=4). Eight samples examined primary school students. The mean effect sizes did not exhibit significant differences based on the education level (Q_B= 4.931, *df*=2, p=0.085). Significant effects were observed for all educational levels: primary school (g=0.573**), middle school (g=0.767***), and high school (g=1.244***) students.

Regarding treatment duration, eleven samples took place interventions less than ten hours (coded as 'short' (g=0.646***), and five samples underwent interventions exceeding ten hours (coded as 'long') (g=0.723***). The other articles did not report the intervention duration. Effect sizes were not significantly different across the intervention duration (Q_B= 0.114, *df*=1 p=0.735), which implies that the length of AR use does not impact the relationship between AR intervention and

Table 4 Moderator analysis for research characteristics variable

Moderator variable	Subgroup	K	Effect size		95% CI		Between-groups effect
			g	SE	LL	UL	
Math domain	NA	5	0.631**	0.228	0.185	1.077	Q_B= 0.527 p=0.468
	GM	19	0.818***	0.119	0.584	1.051	
Education level	Primary	8	0.573**	0.173	0.234	0.911	Q_B= 4.931 p=0.085
	Middle	12	0.767***	0.136	0.500	1.034	
	High	4	1.244***	0.249	0.757	1.732	
Treatment Duration	Short	11	0.646***	0.130	0.391	0.900	Q_B= 0.114 p=0.735
	Long	5	0.723***	0.187	0.356	1.090	

CI confidence interval, *SE* standard error, *LL* lower limit, *UL* upper limit, *NA* number and algebra, *GM* geometry and measurement. The sum of k was not 25, as some studies did not report the information of moderator variables. *** $p<0.001$, ** $p<0.01$, * $p<0.05$

K-12 student mathematics achievement. This result implies that regardless of the duration of the time, AR positively influences student mathematics achievement.

AR Feature Variables

The moderator analysis on AR feature variables was presented in Table 5. Regarding connectivity, 16 samples did not use the trigger image marker (which indicates a strong level of connectivity, g = 0.823***), while seven samples used this feature (weak connectivity, g = 0.680**). There was no significant difference between the two groups (Q_B = 0.362, *df* = 1, p = 0.547), which implies that the use of marker-based AR systems or not is not a significant factor in influencing the relationship between AR use and K-12 student mathematics achievement.

In terms of integration of virtual objects, 12 samples used AR devices supporting the capacity to visualize invisible mathematics concepts or unobservable events (g = 0.968***), while 11 samples used AR devices that did not offer such a feature (g = 0.562***). Significant difference was observed between them (Q_B = 3.998, *df* = 1, p = 0.046). These findings indicated that students' mathematics achievement

Table 5 Moderator analysis for AR feature variables

Moderator variable	Subgroup	K	Effect size		95%CI		Between-groups effect
			g	SE	LL	UL	
Connectivity	Weak	7	0.680**	0.199	0.290	1.071	Q_B= 0.362 p=0.547
	Strong	16	0.823***	0.130	0.569	1.078	
Integration of virtual objects	No	11	0.562***	0.148	0.272	0.853	Q_B= 3.998* p=0.046
	Yes	12	0.968***	0.138	0.697	1.238	

CI confidence interval, *SE* standard error, *LL* lower limit, *UL* upper limit. The sum of k was not 25, as some studies did not report the information of moderator variables. *** $p<0.001$, ** $p<0.01$, * $p<0.05$

with AR use was influenced by the AR's affordance of displaying imperceptible mathematics concepts or event via virtual objects.

Discussion and Implications

Recently, there has been a growing interest in education to use AR to support the learning of students (Cai et al., 2022; Chang et al., 2022). However, little is known about the effects of AR use on the mathematics achievement of K–12 students. Considering the influence of mathematics achievement on academic success and societal engagement (Skovsmose, 2019), this study conducted a meta-analysis to determine the effects of AR use on the mathematics achievement of K–12 students. We implemented a meta-analysis involving 22 studies with 25 different samples and found a medium effect size (g = 0.765). That is, the two groups (AR use vs. non-AR use) differ by 0.75 standard deviation in mathematics achievement.

Usually, the introduction of new educational innovations positively influences student achievement, with an effect size of around 0.4 (Hattie, 2008). This is because teachers' enthusiasm for using the innovations, along with students' engagement and excitement, enhances student achievement (Hilton, 2018; Jiang et al., 2025). Moreover, Hillmayr et al. (2020) examined 33 studies and reported a medium effect size (g = 0.55) regarding the effects of digital tools (e.g., tutoring systems, intelligent tutoring systems, simulations, virtual reality, and hypermedia systems) on student mathematics achievement. The value of our effect size (g = 0.765) was found to be greater than that reported by Hattie (2008) (g = 0.4) and Hillmayr et al. (2020) (g = 0.55), which implies a positive impact of AR use. We suggest future studies explicitly compare the effects of various digital tools, including AR, on student mathematics achievement.

This positive outcome can be explained by the benefits that AR offers in mathematics education. NCTM (2000) stated that "technology is essential in teaching and learning mathematics, as it influences the mathematics that is taught and enhances students' learning" (p. 24). When students use technological tools, they can easily visualize mathematical objects, investigate mathematical ideas, and organize data. Consequently, they can reflect, reason, examine, and evaluate various mathematical concepts and improve problem-solving abilities. AR can provide such learning experiences. As explained by Bujak et al. (2013), AR helps students bridge abstract mathematical concepts with concrete objects with a monitor-based interface. Moreover, AR systems can serve as supportive tools for enhancing "creative thinking, collaboration, problem-solving skills, and communication" (Hidajat, 2024, p. 1005) in mathematics classroom due to their ability to generate creative learning media that leverage virtual content and real-world views simultaneously, in real-time (Lin et al., 2013).

This finding aligns with previous meta-analyses that reported a significant effect of AR on student achievement (Cohen, 1988), including overall student academic achievement (Özdemir et al., 2018, g = 0.517), science achievement of K-12 students (Kalemkuş & Kalemkuş, 2023, g = 0.643), and mathematics achievement of K-12 students (g = 0.407, Li et al., 2021). However, the magnitude of effect size in the present study is nearly double than that of Li et al. (2021). This difference may stem from variations in the data extraction process. Li et al. collected articles published before 2021, whereas our study included articles published up to July 2023. Thus, Li et al. examined nine samples, while we analyzed 25 samples. Therefore, it would be safe to conclude that while the effect of AR on mathematics achievement of K-12 students is significant, the magnitude may vary depending on the data extraction process and the data collected.

Considering the heterogeneity of the samples (Borenstein et al., 2009), we examined the effects of five moderating variables. The three research characteristics variables, namely mathematics domain, education level, and treatment duration, did not show significant moderate effects. For the mathematics domain variable, this study did not find a significant difference between groups. Li et al. (2021) argued that the influence of AR in education varied based on subject areas, as the knowledge and concepts required in each subject differ. However, our finding that exhibited no moderating effect of mathematics domains may be due to the fact that mathematical knowledge, concepts, and tasks are related to visual information in most mathematical domains (NCTM, 2000). As the virtual objects created by AR help students understand mathematical knowledge, concepts, and tasks with greater ease (del Cerro Velázquez & Morales Méndez 2021) across various mathematics domains, the differences between these mathematics domains were not significant.

The non-significant moderating effect of education level has been consistently reported in the prior meta-analysis studies (e.g., Chang et al., 2022; Li et al., 2021; Özdemir et al., 2018). These findings might be attributed to the benefits of AR compared to other tools such as computer and software (e.g., Cabri and GeoGebra). Students can use AR features with limited prior training and knowledge due to its intuitive interface, unlike other technological devices and software. Moreover, students can more easily access and use AR systems with the prevalence of handheld devices such as smartphones and tablets (Demitriadou et al., 2020). Consequently, the effects of AR use on the mathematics achievement of K–12 students, regardless of their education levels, were significantly positive.

Our study found no significant difference between short and long-duration groups. Chang et al. (2022) reported a positive relationship between treatment duration and student cognitive development in a meta-analysis that included 134 articles. Similarly, Li et al. (2021) examined 40 samples and found that increased treatment duration is likely to make students more familiar with AR functions, improving their educational achievement. However, our results revealed different outcomes. These findings may be attributed to data limitation: only 16 out of 25 samples (64%) reported treatment durations. With a limited range of treatment durations in our samples, our finding diverged from previous studies (e.g., Li et al., 2021).

Regarding AR feature variables, the moderating effect of connectivity was not significant. This result may be attributed to the fact that all the studies in our analysis were conducted in a classroom setting, regardless of their use of a trigger image. Location-based AR typically relies on the GPS location of a device to determine whether computer-generated information should be superimposed. This type of AR has the potential to extend mathematics learning beyond the classroom (Ibáñez &

Delgado-Kloos, 2018). However, as all our sample studies conducted in the classroom, it may make it difficult to detect statistical significance between studies with and without trigger images. This finding suggests the need for further research employing location-based AR, conducted at locations outside the classroom, to determine whether a more connected, ubiquitous, and integrated learning approach impacts mathematics achievement.

However, we observed a significant moderating effect of integration of virtual objects, indicating a more favorable impact on mathematics achievement of K-12 students compared to the studies without this feature. This favorable effect may be attributed to the real-time supplementary information provided by AR, enhancing a deeper understanding of the mathematical concepts (del Cerro Velázquez & Morales Méndez, 2021). For instance, Gargrish et al. (2022) demonstrated that their AR software, featuring virtual three-axis representations, aided students in understanding vector algebra and facilitating memory attention due to its affordance of visualization. Therefore, our study suggests that specific AR affordances (e.g., integration of virtual objects) could support mathematics learning of K-12 students, and mathematics educators should consider those elements when designing and implementing AR.

Conclusions and Limitations

The results from our study provide evidence-based findings and assist researchers and educators in understanding the current status of AR in mathematics achievement and identifying future research and practical directions. This study contributes to the existing literature in three ways. First, it examines the overall mean effect size of AR in the context of mathematics education using a meta-analysis. Unlike previous studies that focused on overall subject domain (e.g., Chang et al., 2022), our study only focused on mathematics achievement and synthesizes findings from various experimental studies conducted at different times and places with different samples. Second, this study focused on K-12 students. As most previous meta-analysis studies have examined the effects of AR use on all educational level (e.g., Chang et al., 2022; Özdemir et al., 2018; Tekedere & Göke, 2016), we have little information about how AR influence mathematics learning of K-12 students. The findings of the current study could confirm previous studies on the effects AR on student achievement. Third, this study extended previous meta-analysis on the impact of AR in education (e.g., Chang et al., 2022; Li et al., 2021; Özdemir et al., 2018; Tekedere & Göke, 2016) and examined the effects of various moderating variables, including three research characteristic variables and two AR feature variables, which were rarely examined in the previous studies.

As implications for researchers, first, further research should involve quasi-experimental studies with accurate reporting of statistical information. Out of the initial 2,178 articles retrieved from four databases, only 22 articles remained as final data due to the majority of studies lacking control groups as their sample and failing to provide sufficient statistical information. However, given the increasing popularity of AR application and the need to assess its effectiveness on mathematics achievement, more quasi-experimental studies that provided detailed statistical information are needed. We also want to note that in employing an experimental study, ethical concerns should be considered to benefit both the experimental and comparison groups. One practical approach, proposed by Taber (2019) is that researchers provide an innovation to the control group after the study, or implementing a research design where all participants experience the experimental condition at some stage during the study.

Second, while we found the significant effect of AR use on K-12 student mathematics achievement, we encourage readers to cautiously interpret the maintenance of those effects. More than half of the articles (52%, n = 13) analyzed for this study did not report the timing of their post-tests precisely, while nine articles (36%) reported that they measured the change in achievement immediately after completing the intervention. We suggest that future studies not only report the time interval between the completion of the AR intervention and the test implementation but also study the effect maintained over a sustained period.

Third, researchers conducting meta-analysis can create a more nuanced understanding by examining the moderating effects of AR feature variables. Many previous studies focused on research characteristics variables (e.g., educational level and treatment duration), neglecting AR feature variables. For this reason, this study offers a valuable insight into the moderating effects of AR feature variables. On the flip side, we could not compare our study findings to previous meta-analyses on AR feature variables. Future research should examine the moderating effects of various AR feature variables to provide information on how to implement AR effectively in the context of mathematics education. For example, the empirical studies utilized for the dataset of this study did not report information of how teachers plan and practice for the integration of AR tools. Consequently, the findings of our study may differ if we had examined the influences of those variables. Considering the ways teachers plan and practice for the integration of AR tools on mathematics achievement is an important variable (Tzima et al., 2019), future empirical studies need to report the roles of teachers in detail. This information allows researchers to examine the moderating effects of teachers' instructional practices on the relationship between AR integration and mathematics achievement.

Fourth, when developing AR applications, researchers need to consider integrating virtual objects. As demonstrated in our study, students achieved higher mathematics scores when using this AR feature. Given the positive moderating effect on the relationship between this feature and mathematics achievement of K-12 student, we encourage AR software designers and researchers to explore the inclusion of this feature and document its potential impact on their intended goals in mathematics teaching and learning.

As practical implications, teachers need opportunities to acquire the relevant knowledge and skills to incorporate AR effectively into their mathematics lessons. This can be achieved through various learning opportunities, including teacher education programs and professional development. School leaders also be prepared to allocate financial resources for the acquisition of AR software and relevant devices (e.g., iPad) to ensure that all students have access to AR to support their mathematics learning.

Despite these contributions, this study has three limitations, each suggesting further studies. First, the current study was constrained to include 22 studies comprising 25 samples. Given that the use AR on mathematics education is in the initial stage, caution is needed when interpreting results with a focus on generalization. Second, due to the recent development of AR, the articles included in this study covered a specific time frame (2010—July 2023). As the integration of AR in mathematics education continues to grow, periodic meta-analyses are needed to determine whether the findings in this study hold true in the future. Third, this study only collected articles written in English. Researchers including articles in non-English languages may produce different findings.

Concluding Statement

AR has increasingly become an accessible technology with broad applications across various aspects of daily life, including education. Many governments, educational institutions, and private companies invest substantial resources in adopting AR as a tool to enhance student learning outcomes. This growing popularity necessitates a critical examination of its impact on mathematics education, providing insight into effective strategies for integrating AR into classroom settings.

Our meta-analysis provides robust evidence that incorporating AR in mathematics education positively impacts K-12 student mathematics achievement. Additionally, our findings confirm that the relationship between AR use and student mathematics achievement is not moderated by research-related variables such as mathematics domain, educational level, treatment duration, and AR feature connectivity. This finding implies that AR is a beneficial tool for enhancing student mathematics achievement regardless of variations in these factors. However, we observed a significant moderating effect related to the integration of virtual objects within AR applications. Therefore, educators and researchers implementing AR in mathematics education should consider whether the AR device includes features that display otherwise invisible mathematical concepts or unobservable events through virtual objects. This capability makes AR unique and powerful in improving student achievement in mathematics.

We hope this study establishes a foundation for further investigations into the use of AR in mathematics education and guides educators and researchers toward more effective approaches for integrating AR technology in educational settings.

Funding This work was supported by Stonehill College. However, the funding source was not involved in any of research process.

Declarations

Competing interests There are no known conflicts of interest associated with this publication.

References

Abad-Segura, E., Gonzalez-Zamar, M. D., Rosa, A. L. D. L., & Morales Cevallos, M. B. (2020). Sustainability of educational technologies: An approach to augmented reality research. *Sustainability, 12*(10), 4091. https://doi.org/10.3390/su12104091

Abdul Hanid, M. F., Mohamad Said, M. N. H., Yahaya, N., & Abdullah, Z. (2022). Effects of augmented reality application integration with computational thinking in geometry topics. *Education and Information Technologies, 27*(7), 9485–9521. https://doi.org/10.1007/s10639-022-10994-w

Aldalalah, O., Ababneh, Z., Bawaneh, A., & Alzubi, W. (2019). Effect of augmented reality and simulation on the achievement of mathematics and visual thinking among students. *International Journal of Emerging Technologies in Learning, 14*(18), 164–185. https://doi.org/10.3991/ijet.v14i18.10748

Angraini, L. M., Yolanda, F., & Muhammad, I. (2023). Augmented reality: The improvement of computational thinking based on students' initial mathematical ability. *International Journal of Instruction, 16*(3), 1033–1054. https://doi.org/10.56855/intel.v2i1.176

Arvanitaki, M., & Zaranis, N. (2020). The use of ICT in teaching geometry in primary school. *Education and Information Technologies, 25*(6), 5003–5016. https://doi.org/10.1007/s10639-020-10210-7

Azuma, R. T. (1997). A survey of augmented reality. *Presence, 6*(4), 355–385. https://doi.org/10.1162/pres.1997.6.4.355

Baltacı, Ş, & Çetin, S. (2022). The effect of augmented reality on achievement and spatial visualization skills in technical drawing course. *Journal of Learning and Teaching in Digital Age, 7*(2), 250–259. https://doi.org/10.53850/joltida.1047477

Bernard, R. M., Abrami, P. C., Lou, Y., Borokhovski, E., Wade, A., Wozney, L., Wallet, P. A., Fiset, M., & Huang, B. (2004). How does distance education compare with classroom instruction? A meta-analysis of the empirical literature. *Review of Educational Research, 74*(3), 379–439. https://doi.org/10.3102/00346543074003379

Billinghurst, M., Clark, A., & Lee, G. (2015). A survey of augmented reality. *Foundations and Trends® in Human–Computer Interaction, 8*(2–3), 73–272. https://doi.org/10.1561/1100000049

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). *Introduction to meta-analysis*. John Wiley & Sons Ltd.

Bray, A., & Tangney, B. (2017). Technology usage in mathematics education research: A systematic review of recent trends. *Computers & Education, 114*, 255–273. https://doi.org/10.1016/j.compedu.2017.07.004

Brito, P. Q., & Stoyanova, J. (2018). Marker versus markerless augmented reality: Which has more impact on users? *International Journal of Human-Computer Interaction, 34*(9), 819–833. https://doi.org/10.1080/10447318.2017.1393974

Bujak, K. R., Radu, I., Catrambone, R., MacIntyre, B., Zheng, R., & Golubski, G. (2013). A psychological perspective on augmented reality in the mathematics classroom. *Computers & Education, 68*, 536–544. https://doi.org/10.1016/j.compedu.2013.02.017

Cai, S., Liu, E., Shen, Y., Liu, C., Li, S., & Shen, Y. (2020). Probability learning in mathematics using augmented reality: Impact on student's learning gains and attitudes. *Interactive Learning Environments, 28*(5), 560–573. https://doi.org/10.1080/10494820.2019.1696839

Cai, Y., Pan, Z., & Liu, M. (2022). Augmented reality technology in language learning: A meta-analysis. *Journal of Computer Assisted Learning, 38*(4), 929–945. https://doi.org/10.1111/jcal.12661

Cetintav, G., & Yilmaz, R. (2023). The effect of augmented reality technology on middle school students' mathematic academic achievement, self-regulated learning skills, and motivation. *Journal of Educational Computing Research, 61*(7), 1483–1504. https://doi.org/10.1177/07356331231176022

Chang, H. Y., Binali, T., Liang, J. C., Chiou, G. L., Cheng, K. H., Lee, S. W. Y., & Tsai, C. C. (2022). Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers & Education, 191*, 104641. https://doi.org/10.1016/j.compedu.2022.104641

Chen, Y. C. (2019). Effect of mobile augmented reality on learning performance, motivation, and math anxiety in a math course. *Journal of Educational Computing Research, 57*(7), 1695–1722. https://doi.org/10.1177/0735633119854036

Cheng, C. H., Yang, F. Y., Bhagat, K. K., Liou, W. K., Chang, C. Y., & Zhang, Y. (2018). Investigating the learning performance toward geometry learning in an augmented reality system. In M. Rodrigo, J. Yang, L. Wong, & M. Chang (Eds.), *Proceedings of the 26th International Conference on Computers in Education* (pp. 337–339). Asia-Pacific Society for Computers in Education.

Cheung, A. C., & Slavin, R. E. (2013). The effectiveness of educational technology applications for enhancing mathematics achievement in K-12 classrooms: A meta-analysis. *Educational Research Review, 9*, 88–113. https://doi.org/10.1016/j.edurev.2013.01.00

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Erlbaum.

del Cerro Velázquez, F., & Morales Méndez, G. (2021). Application in augmented reality for learning mathematical functions: A study for the development of spatial intelligence in secondary education students. *Mathematics, 9*(4), 369. https://doi.org/10.3390/math9040369

Demitriadou, E., Stavroulia, K. E., & Lanitis, A. (2020). Comparative evaluation of virtual and augmented reality for teaching mathematics in primary education. *Education and Information Technologies, 25*, 381–401. https://doi.org/10.1007/s10639-019-09973-5

Drury-Stotz, M. (2018). *"Creature counting": The effects of augmented reality on perseverance and early numeracy skills* (ERIC document ED586590) [Doctoral dissertation, Lehigh University]. ProQuest Dissertations & Theses.

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing, 62*(1), 107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x

Erasmus Research institute of Management (n.d.). *Failsafe-N tests*. Retrieved June 8, 2024 from https://www.erim.eur.nl/research-support/meta-essentials/user-manual/work-with-the-workbooks/publication-bias-analysis-sheet/failsafe-n-tests/

Estapa, A., & Nadolny, L. (2015). The effect of an augmented reality enhanced mathematics lesson on student achievement and motivation. *Journal of STEM education, 16*(3), 40–48. https://www.learntechlib.org/p/151963.

Flavin, E., & Flavin, M. (in press). Developing augmented reality system for embodied mathematics learning. In *Proceedings of the 46th Conference of the North American Chapter of the International Group for the Psychology of Mathematics Education* (PME-NA). PME.

Flores-Bascuñana, M., Diago, P. D., Villena-Taranilla, R., & Yáñez, D. F. (2019). On augmented reality for the learning of 3D-geometric contents: A preliminary exploratory study with 6-grade primary students. *Education Sciences, 10*(1), 4. https://doi.org/10.3390/educsci10010004

Gargrish, S., Kaur, D. P., Mantri, A., Singh, G., & Sharma, B. (2021). Measuring effectiveness of augmented reality-based geometry learning assistant on memory retention abilities of the students in 3D geometry. *Computer Applications in Engineering Education, 29*(6), 1811–1824. https://doi.org/10.1002/cae.22424

Gargrish, S., Mantri, A., & Kaur, D. P. (2022). Evaluation of memory retention among students using augmented reality based geometry learning assistant. *Education and Information Technologies, 27*(9), 12891–12912. https://doi.org/10.1007/s10639-022-11147-9

Gecu-Parmaksiz, Z., & Delialioglu, O. (2019). Augmented reality-based virtual manipulatives versus physical manipulatives for teaching geometric shapes to preschool children. *British Journal of Educational Technology, 50*(6), 3376–3390. https://doi.org/10.1111/bjet.12740

Hattie, J. (2008). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement*. Routledge.

Hedges, L. V., & Olkin, I. (2014). *Statistical methods for meta-analysis*. Academic Press.

Hidajat, F. A. (2024). Augmented reality applications for mathematical creativity: A systematic review. *Journal of Computers in Education, 11*, 991–1040. https://doi.org/10.1007/s40692-023-00287-7

Higgins, J. P., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *BMJ, 327*(7414), 557–560. https://doi.org/10.1136/bmj.327.7414.557

Hillmayr, D., Ziernwald, L., Reinhold, F., Hofer, S. I., & Reiss, K. M. (2020). The potential of digital tools to enhance mathematics and science learning in secondary schools: A context-specific meta-analysis. *Computers & Education, 153*, 103897. https://doi.org/10.1016/j.compedu.2020.103897

Hilton, A. (2018). Engaging primary school students in mathematics: Can iPads make a difference?. *International Journal of Science and Mathematics Education, 16*(1), 145–165. https://doi.org/10.1007/s10763-016-9771-5

Hwang, W. Y., Nurtantyana, R., Purba, S. W. D., & Hariyanti, U. (2023). Augmented reality with authentic GeometryGo App to help geometry learning and assessments. *IEEE Transactions on Learning Technologies, 16*(5), 769–779. https://doi.org/10.1109/tlt.2023.3251398

Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education, 123*, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Ibáñez, M. B., Portillo, A. U., Cabada, R. Z., & Barrón, M. L. (2020). Impact of augmented reality technology on academic achievement and motivation of students from public and private Mexican schools. A case study in a middle-school geometry course. *Computers & Education, 145*, 103734. https://doi.org/10.1016/j.compedu.2019.103734

Ibili, E., Çat, M., Resnyansky, D., Şahin, S., & Billinghurst, M. (2020). An assessment of geometry teaching supported with augmented reality teaching materials to enhance students' 3D geometry thinking skills. *International Journal of Mathematical Education in Science and Technology, 51*(2), 224–246. https://doi.org/10.1080/0020739X.2019.1583382

Jiang, H., Chugh, R., Turnbull, D., Wang, X., & Chen, S. (2025). Exploring the effects of technology-related informal mathematics learning activities: A structural equation modeling analysis. *International Journal of Science and Mathematics Education, 23*(1), 49–69. https://doi.org/10.1007/s10763-024-10456-4

Kalemkuş, J., & Kalemkuş, F. (2023). Effect of the use of augmented reality applications on academic achievement of student in science education: Meta-analysis review. *Interactive Learning Environments, 31*(9), 6017–6034. https://doi.org/10.1080/10494820.2022.2027458

Kavaz, S., & Kocak, O. (2024). The effect of the online flipped learning model on secondary school students' academic achievement, attitudes towards their mathematics course, and cognitive load. *International Journal of Science and Mathematics Education, 22*(8), 1709–1737. https://doi.org/10.1007/s10763-024-10455-5

Koparan, T., Dinar, H., Koparan, E. T., & Haldan, Z. S. (2023). Integrating augmented reality into mathematics teaching and learning and examining its effectiveness. *Thinking Skills and Creativity, 47*, 101245. https://doi.org/10.1016/j.tsc.2023.101245

Korkmaz, E., & Morali, H. S. (2022). A meta-synthesis of studies on the use of augmented reality in mathematics education. *International Electronic Journal of Mathematics Education, 17*(4), em0701. https://doi.org/10.29333/iejme/12269

Li, F., Wang, X., He, X., Cheng, L., & Wang, Y. (2021). How augmented reality affected academic achievement in K-12 education: A meta-analysis and thematic-analysis. *Interactive Learning Environments, 31*(9), 5582–5600. https://doi.org/10.1080/10494820.2021.2012810

Lin, H. C. K., Chen, M. C., & Chang, C. K. (2015). Assessing the effectiveness of learning solid geometry by using an augmented reality-assisted learning system. *Interactive Learning Environments, 23*(6), 799–810. https://doi.org/10.1080/10494820.2013.817435

Lin, T.-J., Duh, H.B.-L., Li, N., Wang, H.-Y., & Tsai, C.-C. (2013). An investigation of learners' collaborative knowledge construction performances and behavior patterns in an augmented reality simulation system. *Computers & Education, 68*, 314e321. https://doi.org/10.1016/j.compedu.2013.05.011

Linden, A. H., & Hönekopp, J. (2021). Heterogeneity of research results: A new perspective from which to assess and promote progress in psychological science. *Perspectives on Psychological Science, 16*(2), 358–376. https://doi.org/10.1177/1745691620964193

López-Belmonte, J., Moreno-Guerrero, A. J., López-Núñez, J. A., & Hinojo-Lucena, F. J. (2023). Augmented reality in education: A scientific mapping in Web of Science. *Interactive Learning Environments, 31*(4), 1860–1874. https://doi.org/10.1080/10494820.2020.1859546

Maass, K., Sorge, S., Romero-Ariza, M., Hesse, A., & Straser, O. (2022). Promoting active citizenship in mathematics and science teaching. *International Journal of Science and Mathematics Education, 20*(4), 727–746. https://doi.org/10.1007/s10763-021-10182-1

Majid, S. N. A., & Salam, A. R. (2021). A systematic review of augmented reality applications in language learning. *International Journal of Emerging Technologies in Learning, 16*(10), 18–34. https://doi.org/10.3991/ijet.v16i10.17273

Medina Herrera, L., Castro Pérez, J., & Juárez Ordóñez, S. (2019). Developing spatial mathematical skills through 3D tools: Augmented reality, virtual environments and 3D printing. *International Journal on Interactive Design and Manufacturing, 13*, 1385–1399. https://doi.org/10.1007/s12008-019-00595-2

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLOS Medicine, 151*(4), 264–269. https://doi.org/10.1371/journal.pmed.1000097

Moses, R., & Cobb, C. (2001). *Radical equations: Math literacy and civil rights*. Beacon Press.

Nadzri, A. Y. N. M., Ayub, A. F. M., & Zulkifli, N. N. (2023). The effect of using augmented reality module in learning geometry on mathematics performance among primary students. *International Journal of Information and Education Technology, 13*(9), 1478–1486. https://doi.org/10.18178/ijiet.2023.13.9.1952

National Council of Teachers of Mathematics [NCTM] (2000). *Principles and standards for school mathematics*. Author.

National Council of Teachers of Mathematics [NCTM] (2011). *Technology in teaching and learning mathematics*. NCTM.
Özdemir, M., Sahin, C., Arcagok, S., & Demir, M. K. (2018). The effect of augmented reality applications in the learning process: A meta-analysis study. *Eurasian Journal of Educational Research, 18*(74), 165–186. https://doi.org/10.14689/ejer.2018.74.9
Parekh, P., Patel, S., Patel, N., & Shah, M. (2020). Systematic review and meta-analysis of augmented reality in medicine, retail, and games. *Visual Computing for Industry, Biomedicine, and Art, 3*, 1–20. https://doi.org/10.1186/s42492-020-00057-7
Poçan, S., Altay, B., & Yaşaroğlu, C. (2023). The effects of mobile technology on learning performance and motivation in mathematics education. *Education and Information Technologies, 28*(1), 683–712. https://doi.org/10.1007/s10639-022-11166-6
Rejeb, A., Rejeb, K., & Treiblmaier, H. (2023). How augmented reality impacts retail marketing: A state-of-the-art review from a consumer perspective. *Journal of Strategic Marketing, 31*(3), 718–748. https://doi.org/10.1080/0965254X.2021.1972439
Sırakaya, M., & Sırakaya, D. A. (2022). Augmented reality in STEM education: A systematic review. *Interactive Learning Environments, 30*(8), 1556–1569. https://doi.org/10.1080/10494820.2020.1722713
Skovsmose, O. (2019). Crisis, critique and mathematics. *Philosophy of Mathematics Education Journal, 35*, 1–16.
Statista. (2024). *Number of mobile augmented reality (AR) active user devices worldwide from 2019 to 2024*. https://www.statista.com/statistics/1098630/global-mobile-augmented-reality-ar-users/
Taber, K. S. (2019). Experimental research into teaching innovations: Responding to methodological and ethical challenges. *Studies in Science Education, 55*(1), 69–119. https://doi.org/10.1080/03057267.2019.1658058
Tekedere, H., & Göke, H. (2016). Examining the effectiveness of augmented reality applications in education: A meta-analysis. *International Journal of Environmental and Science Education, 11*(16), 9469–9481. https://files.eric.ed.gov/fulltext/EJ1118774.pdf.
Tsuei, M., & Chiu, J. I. (2021). Using a mobile augmented reality app on mathematics word problems for children. In K. Masaaki (Ed), *International Conference on Human-Computer Interaction* (pp. 302–306). Springer. https://doi.org/10.1007/978-3-030-90179-0_39
Tzima, S., Styliaras, G., & Bassounas, A. (2019). Augmented reality applications in education: Teachers point of view. *Education Sciences, 9*(2), 99. https://doi.org/10.3390/educsci9020099
Wang, L., Zhang, Q., & Sun, D. (2025). Exploring the impact of an augmented reality-integratedmathematics curriculum on students' spatial skills in elementary school. *International Journal of Science and Mathematics Education, 23*(2), 387–414. https://doi.org/10.1007/s10763-024-10473-3
Wu, H. K., Lee, S. W. Y., Chang, H. Y., & Liang, J. C. (2013). Current status, opportunities and challenges of augmented reality in education. *Computers & Education, 62*, 41–49. https://doi.org/10.1016/j.compedu.2012.10.024
Yousef, A. M. F. (2021). Augmented reality assisted learning achievement, motivation, and creativity for children of low-grade in primary school. *Journal of Computer Assisted Learning, 37*(4), 966–977. https://doi.org/10.1111/jcal.12536

Authors and Affiliations

Eunhye Flavin[1] · **Sunghwan Hwang**[2] · **Matthew T. Flavin**[3]

✉ Sunghwan Hwang
shwang@cnue.ac.kr

Eunhye Flavin
eflavin@gatech.edu

Matthew T. Flavin
mflavin@gatech.edu

1 Center for Education Integrating Science, Mathematics, and Computing, Georgia Institute of Technology, 505 10th St NW, 30332 Atlanta, Georgia

2 Department of Mathematics Education, Chuncheon National University of Education, 126 Gongji-Ro, Chuncheon-Si, Gangwon-Do, South Korea

3 School of Electrical and Computer Engineering, Georgia Institute of Technology, 777 Atlantic Dr NW, 30332 Atlanta, GA, Georgia