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# The effect of integrating augmented reality (AR) on student's cognitive learning outcomes in science education: A meta-analysis of recent literature

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## Abstract

Augmented Reality (AR) is one of the emerging tools in transforming science education, yet its practical significance on cognitive learning outcomes remains inconsistently documented. This meta-analysis synthesizes empirical evidence of 29 comparisons from 28 empirical studies (2020–2025) to quantify AR's effectiveness and identify moderating factors. Using a random-effects model, we analyzed data from 2,841 secondary school students across scientific disciplines (biology, chemistry, physics, earth/space science). Results revealed a large, significant overall effect size ( $g = 0.98$ , 95% CI [0.74, 1.21]), indicating AR's substantial positive impact on cognitive outcomes. Publication bias tests including Egger's regression, fail-safe N, and Begg and Mazumdar's rank correlation confirmed robust results. Substantial heterogeneity was observed ( $I^2=80.67\%$ ,  $p<.001$ ), leading to moderator analyses, which revealed that discipline and educational level did not significantly influence outcomes. Instructional duration significantly moderated effects, with longer exposures (6–8 weeks) yielding larger effect size ( $g = 1.63$ ) than shorter ones (1–3 weeks;  $g = 0.72$ ). These findings show that AR's benefits are clearest with sustained use, supporting its integration into science curricula. Educators should align AR duration with learning objectives to maximize cognitive gains.

**Keywords:** AR in science education, cognitive learning outcomes, effect size, publication bias

## Introduction

Cognitive learning outcomes are specifically important in science education because they represent the foundational goals of instruction, which are essential for students to engage meaningfully with scientific content. In the context of 21st-century education, fostering



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strong cognitive skills enables learners to apply scientific knowledge critically and creatively across real-world contexts (Drigas & Karyotaki, 2014). As science subjects often involve abstract and complex concepts, students must develop the ability to process, analyze, and retain information effectively. Augmented reality, with its capacity to present interactive and immersive content, is particularly suited to supporting these cognitive processes (Buchner et al., 2022). Therefore, examining the impact of AR on cognitive outcomes offers valuable insights into its pedagogical effectiveness and practical relevance in improving science education.

The use of Augmented Reality (AR) in science pedagogy is emerging as a new way of dealing with the long-standing issue of teaching complex scientific ideas. By overlaying digital information onto the physical world, AR creates immersive learning environments that promote engagement, spatial understanding, and conceptual mastery (Dunleavy & Dede, 2014). Despite its potential, the empirical evidence on AR's impact on cognitive learning outcomes remains fragmented, with studies often reporting statistical significance over practical educational value. This meta-analysis systematically synthesizes existing research to quantify the magnitude of AR's effects and identify the moderators that might influence the magnitude of this effect.

Augmented Reality (AR) is a technology that superimposes digital elements such as 3D models, animations, or informational overlays onto the real-world environment, typically viewed through devices like smartphones, tablets, or AR glasses. It has been applied in various fields, including Science education where it was shown to enhance learning by making abstract or invisible concepts visually interactive and spatially contextualized (Lee, 2012). For example, students can manipulate virtual atoms in chemistry (Liu et al., 2022), explore the human body in biology (Kurniawan et al., 2018), or simulate physics phenomena in real time (Ferrari et al., 2024; Mehmet & Yasemin, 2021). AR merges physical and virtual worlds, thereby transforming passive instruction into active exploration and addressing longstanding challenges in teaching complex scientific topics.

With its affordances, its potential to enhance educational learning outcomes in science has been demonstrated in empirical literature. These outcomes may be in terms of cognitive, affective, and psychomotor domains of learning. Studies indicate that AR's interactive and immersive aspects assist students in visualizing abstract scientific principles, with improved outcomes over conventional teaching (i.e., Setiawaty et al., 2024; Ziden et al., 2022). These improvements can be seen in their engagement levels, knowledge retention, and conceptual understanding. AR also fosters active learning, reduces cognitive load, and strengthens spatial reasoning skills (Buchner et al., 2022). AR's real-time feedback and gamified elements increase motivation and long-term retention of complex topics (Özeren & Top, 2023). The cognitive benefits are especially well-documented, given AR's interactive aspects where students are able to visualize scientific concepts and engage in

constructing knowledge actively (Cheng & Tsai, 2013). Psychomotor skills are also developed through AR's hands-on interactions, such as manipulating virtual lab equipment or conducting simulated experiments.

Despite the reported benefits, the research base remains fragmented. Existing studies differ in how they define and measure cognitive learning outcomes, with variations across scientific disciplines and educational levels. While some emphasize knowledge acquisition or academic achievement, others focus on conceptual understanding or critical thinking. These definitions often reflect discipline-specific priorities, for instance, chemistry education emphasizing conceptual mastery and physics focusing on problem-solving. This variation complicates efforts to compare results across studies or draw meaningful conclusions about the cognitive impact of AR. Identifying the cognitive learning outcomes reported in the literature, will clarify the conceptual scope of AR's educational impact.

The emerging literature on augmented reality (AR) in science education also shows promising but inconclusive evidence regarding the effects of AR on student learning outcomes. While many studies establish the potential for AR to support conceptual understanding, engagement, and problem-solving skills, they fail to show practical significance, whereas others report limited or context-dependent effects, leaving educators uncertain when adopting AR. This disintegration of evidence, along with the accelerated development of AR technologies and their rising usage in classrooms, makes the imperative for a thorough synthesis of existing research even greater. A meta-analysis should be undertaken to analyze systematically across studies, quantify the practical importance of AR interventions, and determine the conditions in which AR significantly improves science education. Therefore, this meta-analysis seeks to answer the following questions:

1. What are the cognitive learning outcomes measured in the integration of AR in Science Education?
2. What is the overall effect of Integrating Augmented Reality on those learning Outcomes?
3. Is there a moderating effect of the following variables in the effect size of AR intervention?
  - a. Educational level,
  - b. Scientific Discipline, and
  - c. Instructional duration?

This study hoped to provide educators with insights into whether AR's benefits justify its adoption in classrooms. The findings will offer evidence-based guidance for optimizing AR integration in science curricula. Ultimately, this research sought to bridge the gap between theoretical potential and practical implementation, ensuring that AR adoption is driven by robust empirical evidence rather than technological trends alone.

## Methodology

### Research design

This research utilized a meta-analysis design to systematically synthesize empirical studies on augmented reality (AR) in science education. The study employed a random-effects model to account for anticipated heterogeneity across educational contexts, intervention types, and outcome measures (Borenstein et al., 2009). The design adhered to PRISMA 2020 guidelines (Page et al., 2021) and prioritized transparency by using explicit inclusion/exclusion criteria and documenting all analytical decisions to enable replication.

### Search strategy

A comprehensive literature search was conducted across six electronic databases: CrossRef (n=594), Google Scholar (n=22), OpenAlex (n=1,001), Scopus (n=190), Semantic Scholar (n=1,000), and ERIC (n=262), using the Boolean search string "augmented reality" AND "science learning" AND "learning outcomes" to capture studies examining AR's impact on science learning outcomes. Additional search using the string "augmented reality" AND "Biology" OR "Physics" OR "Chemistry" OR "Earth Science" AND "learning outcomes" yielded an additional 11,300 results across the databases. The search, limited to peer-reviewed articles published between 2020 and 2025, aimed to balance breadth with relevance. Overall, initial results yielded 14,369 records, which were subsequently deduplicated and screened against predefined eligibility criteria. Database selection prioritized multidisciplinary coverage while minimizing redundancy through iterative keyword testing.

### Eligibility criteria

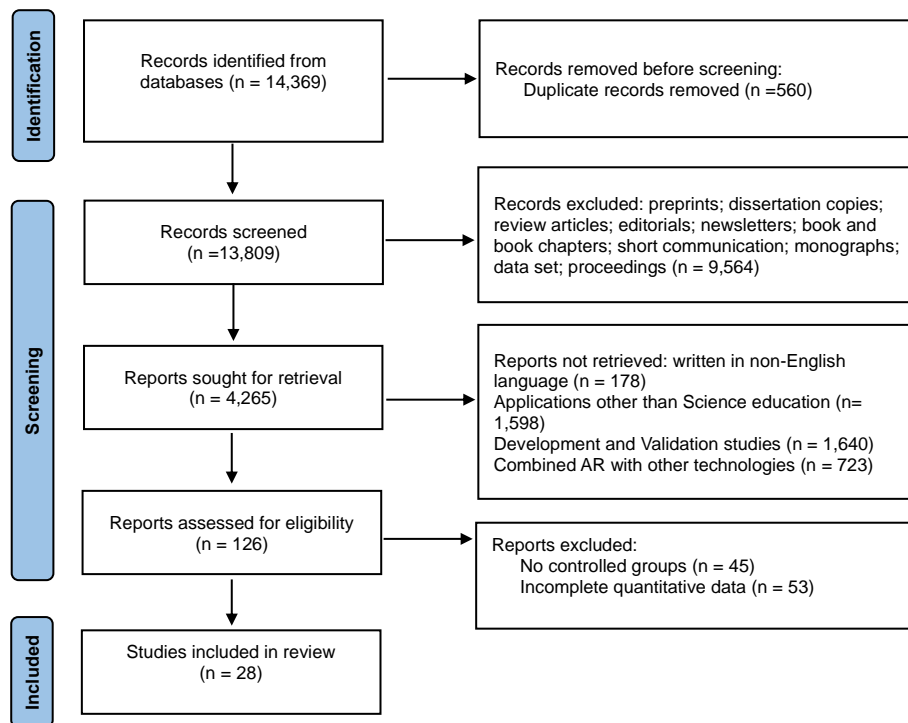
Studies were included if they: (1) were published as peer-reviewed journal articles between 2020–2025, (2) focused on science education for secondary school students, considering they are beginning the formal operational stage, where abstract reasoning emerges but requires support and where foundational abstract concepts are introduced well-suited to AR's visualization affordances, (3) empirically evaluated AR's impact on cognitive learning outcomes using experimental–control group designs, (4) employed pretest–posttest assessments, and (5) reported quantitative data (sample size, means, standard deviations) for meta-analysis. Conversely, studies were excluded if they: (1) were reviews, editorials, books, or book chapters; (2) predated 2020; (3) lacked empirical data; (4) addressed non-science disciplines; (5) did not measure student learning outcomes; or (6) omitted essential quantitative data. These criteria ensured methodological rigor while aligning with the study's focus on measurable cognitive gains from AR interventions.

### Study selection process

The study selection process adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines and involved three systematic stages: Identification, Screening, and Inclusion (Figure 1). The meta-analysis incorporated data from 28 published papers, one of which reported results from two comparisons within the same article. Consequently, a total of 29 distinct study datasets were included in the quantitative synthesis.

**Figure 1**

PRISMA flow of the selection process (Page et al., 2021)



### Data extraction and coding

A systematic data extraction protocol was developed to ensure consistency and accuracy in capturing relevant study characteristics. The following variables were coded for each included study using the MS Excel program: 1) study identification which includes the author, publication year, and country of implementation; 2) study details including types of AR platforms, educational level, discipline, study duration, and cognitive outcomes measured; 3) Experimental Study data including sample size, mean, and standard deviations for both experimental and control groups. Two researchers independently coded all studies using the standardized coding template. Following individual coding completion, their entries were systematically compared to assess consistency. The inter-rater reliability

analysis yielded a Cohen's  $\kappa$  coefficient of .90, indicating excellent agreement between coders (Viera & Garrett, 2005).

### **Data analysis**

Data analysis was performed using the Comprehensive Meta-Analysis (CMA) software and the MAJOR meta-analysis module in Jamovi (Version 2.5.2). The analysis included three phases. First, effect size calculation, since the studies obtained did not report effect size. Here, standardized mean differences (Hedges'  $g$ ) with 95% confidence intervals were computed for all studies. The interpretation of the effect size followed the recommendations of Cohen (1998) where:

Small Effect:  $0.2 < g < 0.5$

Medium or Moderate Effect:  $0.5 < g < 0.8$

Large Effect:  $g > 0.8$

Next, the overall Effect Size was estimated from the pooled effect size across all studies using the Random effects model (Hedges, 1984), accounting for anticipated heterogeneity across study designs and contexts. Heterogeneity was then formally assessed using the  $I^2$  statistic and Cochran Q-statistic ( $Q^T$ ) to quantify between-study variance, with values exceeding 75% indicating substantial variability (Higgins & Thompson, 2002). Next, publication bias was evaluated through visual inspection of funnel plots, Fail-Safe N Calculation, Egger's Test, Begg and Mazumdar's rank correlation. Finally, a moderator analysis was conducted to identify variables that significantly influenced effect sizes, including educational level, scientific discipline, and instructional duration.

## **Results and discussions**

### **The cognitive learning outcomes measured**

The integration of Augmented Reality (AR) in science education has garnered attention for its potential to enhance cognitive learning outcomes among students. Cognitive learning outcomes refer to the knowledge and skills that students acquire through educational experiences, particularly in understanding complex scientific concepts. The following are the operational definitions of cognitive learning outcomes in the context of the studies as summarized in Table 1.

**Table 1**

Cognitive learning outcomes measured in AR intervention

Discipline	Educ Level	AR Platform	Study Location	Cognitive Outcomes measured	Reference
Earth and Space	Junior HS	mobile	Jordan	Creative Thinking	(AlAli et al., 2025)
Physics	Senior HS	mobile	Kazakhstan	Academic Achievement	(Arymbekov et al., 2023)
Physics	Junior HS	mobile	Kazakhstan	Academic success	(Arymbekov et al., 2024)
General Science	Senior HS	mobile	Indonesia	Knowledge	(Asrizal et al., 2024)
General Science	Junior HS	mobile	India	Knowledge	(Bhardwaj, 2023)
Chemistry	Junior HS	mobile	Taiwan	Conceptual Understanding	(Chen & Liu, 2020)
Biology	Senior HS	mobile	Portugal	Academic Performance	(Faria & Miranda, 2024)
Earth and Space	Junior HS	mobile	Spain	Academic Performance	(Ferrari et al., 2024)
Biology	Junior HS	mobile	Malaysia	Academic Achievement	(Jaballudin & Khalid, 2024)
Earth and Space	Junior HS	mobile	Jordan	Academic Achievement	(Jaber & Alrifaaee, 2022)
Chemistry	Junior HS	mobile	Ukraine	Conceptual Understanding	(Karnishyna et al., 2024)
Physics	Senior HS	mobile	Indonesia	Critical Thinking	(Kurnianto et al., 2024)
Chemistry	Junior HS	mobile	China	Knowledge gains	(Liu et al., 2022)
Earth and Space	Junior HS	mobile	Turkey	Academic achievement	(Mehmet & Yasemin, 2021)
Biology	Junior HS	mobile	Indonesia	Conceptual Understanding	(Pamungkas et al., 2023)
Biology	Senior HS	mobile	Indonesia	Learning	(Rini et al., 2024)
Earth and Space	Junior HS	mobile	Turkey	Academic achievement	(Sahin & Yilmaz, 2020)
Biology	Senior HS	Mobile	Indonesia	Concept Mastery	(Safitri et al., 2024)
Chemistry	Senior HS	mobile	Indonesia	Concept Mastery	(Setiawaty et al., 2024)
Chemistry	Senior HS	mobile	India	Conceptual Understanding	(Singh & Zhang, 2025)
Chemistry	Junior HS	mobile	Vietnam	Academic Performance	(Son et al., 2025)
General Science	Junior HS	mobile	Indonesia	Concept Understanding	(Sutarman et al., 2024)
Earth and Space	Junior HS	mobile	Turkey	Academic achievement	(Talan et al., 2022)
Chemistry	Junior HS	mobile	Taiwan	Learning Achievement	(Tarng et al., 2022)
Biology	Junior HS	mobile	Indonesia	Creative thinking	(Weng et al., 2020)
Biology	Junior HS	mobile	Turkey	Academic Achievement	(Yildirim, 2020)
Physics	Junior HS	mobile	China	Learning Performance	(Yu et al., 2022a) <sup>a</sup>
Physics	Junior HS	mobile	China	Learning Performance	(Yu et al., 2022a) <sup>b</sup>
Biology	Junior HS	mobile	Malaysia	Academic achievement	(Ziden et al., 2022)

Analysis revealed four recurring operational definitions of cognitive learning outcomes in AR-based science education.

**Knowledge Acquisition (Declarative Knowledge).** Cognitive learning outcomes also encompass the retention and gain of knowledge. Several studies (Asrizal et al., 2024; Bhardwaj, 2023; Liu et al., 2022) emphasize knowledge acquisition, focusing on the recall

of factual and declarative information such as terminology or scientific principles- for example, understanding the names and functions of cell structures. These outcomes are typically assessed using standardized tests or quizzes and are most prevalent in junior high school contexts within General Science and Chemistry disciplines.

**Conceptual Understanding.** A second cluster of studies centers on conceptual understanding (Chen & Liu, 2020; Karnishyna et al., 2024; Pamungkas et al., 2023; Setiawaty et al., 2024; Sutarman et al., 2024), which targets students' grasp of abstract and often complex scientific ideas like molecular bonding or system interactions. This type of cognitive outcome was usually measured using tools such as concept inventories and diagram-labeling activities.

**Academic Performance.** Another widely used operational definition is academic performance or learning performance, as seen in numerous studies (Faria & Miranda, 2024; Ferrari et al., 2024; Yildirim, 2020; Yu et al., 2022b). They have also been interchangeable used with Academic Achievement in this context. These terms typically refer to learners' performance as measured by standardized tests, quizzes, or grades following exposure to AR-based instruction. Studies have shown that students using AR applications demonstrate significantly higher academic performance compared to those in traditional learning environments.

**Critical Thinking.** A smaller subset of research investigates higher-order cognitive skills, particularly critical thinking (Kurnianto et al., 2024). These outcomes involve evaluating hypotheses or navigating open-ended problem scenarios and are assessed through scenario-based tasks and open-response formats. This study points to the potential of AR to enhance analytical reasoning and problem-solving, which are cognitive skills that go beyond rote memorization and factual recall.

**Creative Thinking.** Few recent studies extended the investigation of cognitive outcomes to include creative thinking (AlAli et al., 2025). In the context of Earth and Space Science, researchers examined how AR-based instruction might foster students' ability to generate novel ideas, make unique connections, and think flexibly about scientific concepts. This represents an emerging direction in AR research, suggesting that immersive technologies may support not only knowledge acquisition and conceptual understanding but also the development of divergent thinking skills essential for scientific innovation.

Despite the differences in the operational definition of cognitive learning outcomes, the research literature reviewed in this study consistently emphasized the significance of generic skills and competencies, which transcend disciplinary boundaries, for instance, knowledge gains and conceptual understanding. Studies also utilized similar assessment techniques to assess these outcomes particularly with the use of pre-tests and post-tests that allow them to measure the effect of an AR intervention, although varied in terms of cognitive levels. This focus offered a distinct advantage: standardized assessment scales

can facilitate meaningful comparisons of student learning outcomes across diverse academic fields and institutional contexts. Cognitive outcomes were consistently reported as mean scores for both the experimental and control groups, enabling direct comparison across studies. Statistical analyses, such as independent samples *t*-tests (Faria & Miranda, 2024; Sutarman et al., 2024) and Analysis of Covariance (ANCOVA)(Yu et al., 2022a), were commonly used to determine the significance of the observed differences. This methodological consistency allowed for the aggregation of effect sizes, despite variations in content, grade levels, or definitions of cognitive learning. Consequently, the studies met the inclusion criteria for the meta-analysis, as they provided comparable quantitative data suitable for effect size calculation and synthesis.

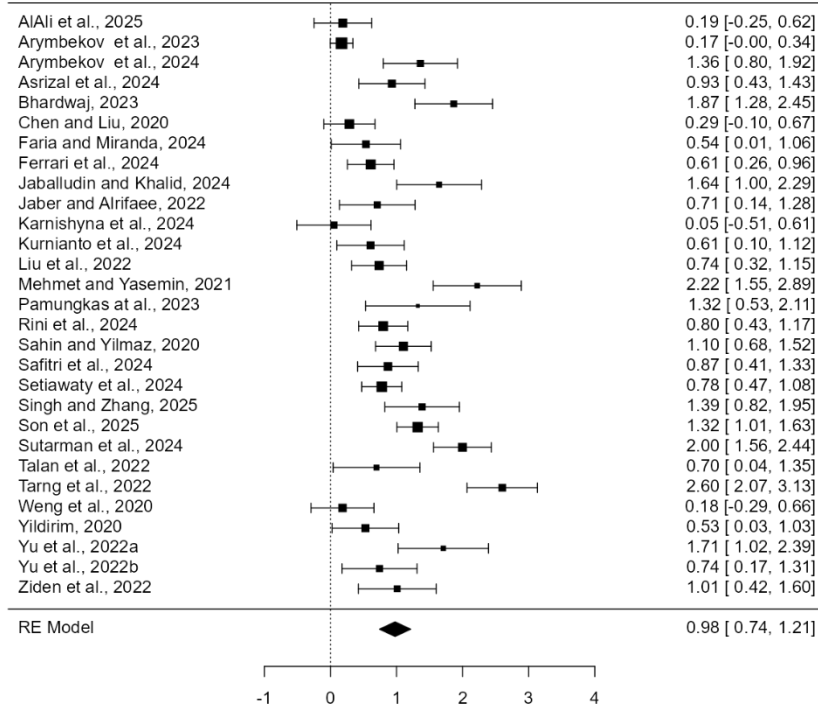
### **Effect of integrating augmented reality on student learning outcomes**

#### ***Overall effect size***

There were 28 qualifying studies, which included a total of 2,841 participants and 29 comparisons. The analysis of effect sizes was conducted using a Random Effects Model, which is appropriate given the anticipated heterogeneity among studies in terms of design, participant characteristics, AR tools, and outcome definitions. Figure 2 presents the forest plot summarizing the effect sizes of 29 comparisons examining the impact of Augmented Reality (AR) on students' cognitive learning outcomes in science education.

**Figure 2**

Forest plot showing the effect size of individual studies and the overall effect size using the random effects model. Values shown at the right are the study effects and their confidence intervals



The overall pooled effect size is 0.98 [95% CI: 0.74, 1.21], represented by the diamond at the bottom of the plot. This result suggests a large and statistically significant positive effect of AR interventions on students’ cognitive learning outcomes, according to conventional benchmarks for interpreting effect sizes (Cohen, 1988). The confidence interval does not cross zero, reinforcing the robustness of this positive finding. This overall effect is consistent with meta-analysis results of Xu et al. (2022) covering the sciences and Mathematics studies published until 2020, however, this present study reported a large effect size compared to their moderate effect. Based on the findings, the integration of Augmented reality into Science learning can improve students’ conceptual understanding, critical thinking, and academic performance— all are manifestations of cognitive learning.

Despite the overall positive trend, variability in the effect sizes among the studies is evident. Some studies, such as Sutarman et al. (2024) (2.00 [1.56, 2.44]) and Mehmet and Yasemin (2021) (2.22 [1.55, 2.89]), reported very large effect sizes, indicating substantial improvements in cognitive outcomes due to AR integration. Tarng et al. (2022) had the largest computed effect size among the included studies. Others, such as Chen and Liu (2020) (0.29 [-0.10, 0.67]), reported smaller effect sizes, with confidence intervals that include zero, suggesting that in some contexts, AR may not produce a measurable impact on learning. The smallest effect size with a confidence interval crossing zero was found in this study. The variation in effect sizes could be influenced by the nature of the science

content being taught, and participant factors such as age, prior knowledge, and engagement levels, thus, justifying the use of the random effects model.

### **Heterogeneity assessment**

While the overall effect size indicates a large positive impact of Augmented Reality on students' cognitive learning outcomes, the noticeable variation in effect sizes across the included studies suggests potential heterogeneity in the data. This variability highlights the importance of examining whether the differences among studies are due to random sampling error or underlying differences in study characteristics. To better understand the extent of this, heterogeneity statistics was calculated. Table 2 below shows the heterogeneity values.

**Table 2**

Values of Heterogeneity Assessment

$Q^T$	df (Q)	p-value	$I^2$ statistic
222.410	28	<0.001	80.67%

Here, the Q test for heterogeneity (Cochran, 1954) and the  $I^2$  statistics were used. The Cochran Q-statistic is  $Q^T = 222.410$ , and the associated p-value is less than .001, indicating that the observed variability in effect sizes is statistically significant and unlikely to be due to random sampling error alone. In other words, there is strong evidence that the differences in effect sizes across studies are not merely by chance. Complementing the Q-test, the  $I^2$  value is 80.67%, which suggests that approximately 81% of the total variation in observed effect sizes is attributable to true heterogeneity rather than random error. According to guidelines by Higgins et al. (2003), this level of  $I^2$  represents substantial heterogeneity, meaning that the effect of AR on cognitive learning outcomes varies considerably across studies. This high degree of heterogeneity justifies the use of a random effects model and suggests that further analyses may be valuable to explore potential moderators influencing the variability in effect sizes.

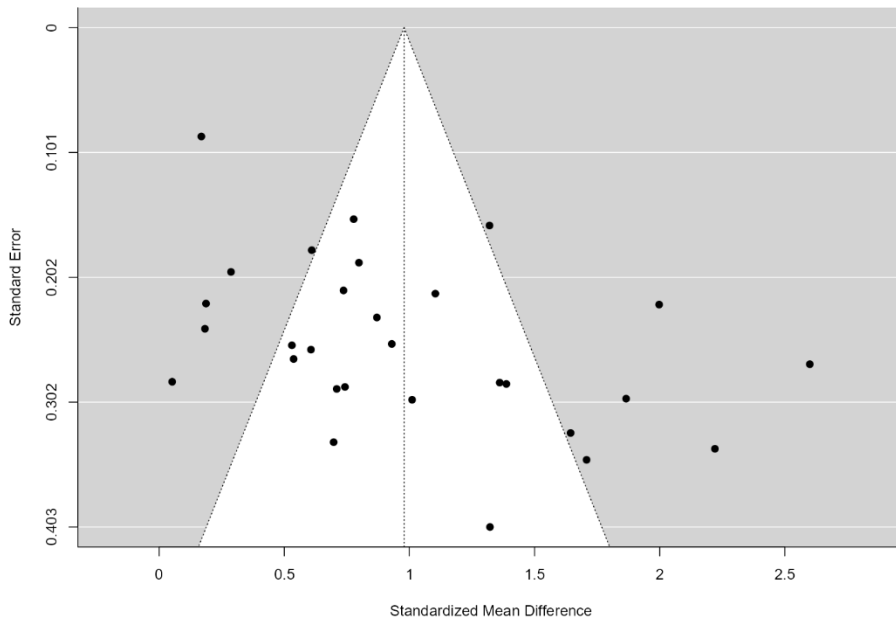
### **Publication bias**

Given the substantial heterogeneity observed among the included studies, it is also important to assess the potential influence of publication bias on the synthesized results. Publication bias occurs when studies with statistically significant or positive findings are more likely to be published, potentially skewing the overall effect estimate (Thornton & Lee, 2000). To evaluate whether such bias could be present in this meta-analysis, several diagnostic tools were employed, including visual inspection of the funnel plot and statistical tests for asymmetry (Lin et al., 2018).

Figure 3 shows the result of the funnel plot. Visual inspection revealed that many studies fall within the funnel-shaped area, indicating a relatively symmetrical distribution of effect sizes around the overall mean. However, 13 out of the 29 studies lie outside the funnel region, suggesting some degree of asymmetry. In this context, this asymmetry may be indicative of a tendency for studies with smaller sample sizes and larger effect sizes to be overrepresented, or for studies with non-significant or smaller effects to be underreported or unpublished (Thornton & Lee, 2000).

**Figure 3**

Funnel plot visually testing for publication bias



While the presence of outliers alone does not confirm publication bias, it does raise concerns about potential distortions in the aggregated effect estimate (Thornton & Lee, 2000). The studies that fall outside the funnel boundaries may reflect true heterogeneity due to methodological differences, variations in intervention implementation, or sample characteristics. Nonetheless, the pattern observed suggests that further investigation is warranted. To better understand whether this asymmetry is statistically significant, additional analyses such as Egger’s regression test, Fail-Safe N, Begg and Mazumbar Rank Correlation, and the Trim-and-Fill method were conducted. Table 3 shows these results.

**Table 3**

Results of the statistical assessment for publication bias

Test Name	value	<i>p</i>
Rosenberg Fail-Safe N	2973.000	<.001
Orwin Fail-Safe N	29.00	<.001
Begg and Mazumdar Rank Correlation	0.276	0.036
Egger's Regression	2.333	0.020
Trim and Fill Number of Studies	0.000	.

Assessment of publication bias revealed evidence of asymmetry in the distribution of effect sizes. Begg and Mazumdar's rank correlation ( $\tau = 0.276$ ,  $p = 0.036$ ) and Egger's regression test ( $t = 2.333$ ,  $p = 0.020$ ) were both statistically significant, suggesting the potential presence of publication bias. However, the trim-and-fill method imputed zero missing studies, indicating that the observed asymmetry does not substantially affect the overall effect size estimate. This suggests that while smaller studies with larger effects may be slightly overrepresented, the pooled effect size of  $g=0.98$  remains robust. Taken together with the visual inspection of the funnel plot, which showed a generally symmetrical distribution with some studies outside the funnel region, the results suggest that publication bias is unlikely to have substantially influenced the overall effect size.

Further, a Rosenberg Fail-Safe N analysis indicated that 2,973 additional studies with null effects would be required to raise the overall  $p$ -value (above 0.05) and render the effect size of this meta-analysis as statistically nonsignificant. This large number provides strong evidence that the meta-analytic findings are not likely due to publication bias. In addition, an Orwin Fail-Safe N analysis was performed to evaluate the sensitivity of the overall effect size to the inclusion of studies with trivial effects (Orwin, 1983). This revealed that 29 unpublished or missing studies with null results would be needed to reduce the observed mean effect size of 0.98 to a negligible level, defined as  $g= 0.20$  to 0.5, based on the guidelines of Cohen (1998). It would take this number of studies with no effect to diminish the practical significance of the findings. While the number is not excessively high, it still reinforces confidence in the practical relevance of the results, particularly considering the positive and consistent trends across the included studies.

The large number of studies in the Rosenberg Fail-Safe N suggests that the observed effect size on student's cognitive learning outcomes in this meta-analysis is highly robust and unlikely to be overturned by unpublished or missing studies. However, its practical significance could be more easily influenced by several studies with minimal or no effect as indicated by the Orwin Fail-Safe N value. Therefore, although the high Rosenberg fail-safe N supports the reliability of the observed findings, the lower Orwin fail-safe N

highlights the need for cautious interpretation, particularly when considering the potential presence of unpublished studies with null effects. Taken together, the results suggest that the meta-analytic findings are generally resilient to bias and provide strong evidence of a meaningful effect, but they also underscore the importance of ongoing research, transparency, and comprehensive reporting to further solidify the empirical foundation for AR integration in science education.

**Moderators of the AR’s overall effect**

Given the substantial heterogeneity among the included studies as indicated by the  $I^2$  statistic, moderator analyses were conducted using a random-effects model to investigate potential sources of variability and to assess the impact of possible moderator variables. Table 4 below shows the results of the moderator analysis.

**Table 4**  
Moderator analysis using the Random Effects Model (k=29)

Moderator	Estimate	SE	Z	CI lower bound	CI upper bound	p	Interpretation
Discipline	0.047	0.086	0.547	-0.122	0.216	0.584	Not a significant moderator
Educational Level	-0.326	0.263	-1.24	-1.841	0.189	0.215	Not a significant moderator
Instructional Duration	0.404	0.149	2.72	0.113	0.696	0.007	Significant

The results of the moderator analysis revealed that Discipline and Educational Level did not significantly influence the effect of augmented reality on students’ cognitive learning outcomes. Meanwhile, instructional duration was a significant moderator with a p-value of 0.007. This suggests that the amount of time students are exposed to AR-based learning experiences can meaningfully influence the magnitude of these outcomes. As a caveat, we recall that the meta-analytic results yielded substantial heterogeneity ( $I^2 = 80.67%$ ), which indicates that the effectiveness AR varies considerably across contexts. High heterogeneity has important implications for statistical power in meta-analysis. High between-study variance reduces the power of moderator analyses by inflating standard errors, making it more difficult to detect significant effects (Hedges & Pigott, 2004). Therefore, the significant moderators we identified (e.g., instructional duration) likely represent robust effects that withstood this reduced power. Conversely, non-significant moderators (e.g., educational level, scientific discipline) should be interpreted cautiously, as their non-significance may reflect insufficient power rather than true absence of influence. Future

research with larger primary studies and standardized reporting would enable more powerful moderator analyses.

The effect sizes of studies according to Instructional duration were then compared by subgroup analysis. They were coded into three based on observed distribution of intervention lengths, namely: 1-3 weeks (short-term implementations), 4-5 weeks (medium term typically aligned with complete instructional units), 6-8 weeks (extended implementations). Studies longer than 8 weeks fall under the third subgroup. The categorization was guided by recommendations of Borenstein & Higgins (2013)(Borenstein & Higgins, 2013) for conducting subgroup analysis. They encouraged at least 3 studies per group ( $k \geq 3$ ) for basic exploratory comparisons to be able to draw meaningful conclusions.

**Table 5**

Effect sizes of different duration of AR intervention

Instructional Duration	<i>k</i>	Effect Size	se	Z	<i>p</i>
1-3 weeks	13	0.72	0.140	5.13	<.001
4-5 weeks	11	0.967	0.200	4.83	<.001
6-8 weeks	5	1.63	0.278	5.86	<.001

The results in Table 5 indicate a positive trend in which longer AR interventions are associated with greater improvements in cognitive learning outcomes. This suggests that extended exposure to AR may allow students more time to engage with, process, and apply the interactive and immersive elements of the technology, potentially leading to deeper understanding and retention of scientific concepts.

The statistical significance of these findings, along with the increasing effect sizes across duration categories, supports the conclusion that instructional duration is a moderator of AR effectiveness. From a pedagogical perspective, these results emphasize the importance of sustained implementation when integrating AR into instructional settings. Short-term interventions, although beneficial, may not fully capitalize on the cognitive benefits that AR can offer. These findings are consistent with existing literature suggesting that time-on-task and extended exposure to immersive learning environments contribute positively to deeper learning and knowledge retention (Cheng & Tsai, 2013). Although this is the case in this study, a similar report by Xu et al. (2022) however, did not find instructional duration to significantly influence learning outcomes. This discrepancy may be due to differences in sample characteristics or how intervention duration was categorized.

Prior studies have also highlighted the cognitive affordances of AR, emphasizing its ability to support visualization of abstract scientific concepts, enhance spatial

understanding, and foster deeper engagement through interactive and immersive experiences (Kurnianto et al., 2024; Schmidthaler et al., 2023; Setiawaty et al., 2024)(Kurnianto et al., 2024; Schmidthaler et al., 2023; Setiawaty et al., 2024). However, short-term interventions may not allow sufficient time for learners to fully adapt to the integration of AR, potentially limiting the depth of cognitive processing. This could be one factor why longer interventions produced a larger effect size on cognitive outcomes. For instance, Simsek et al. (2025) argue that while AR initially stimulates curiosity and motivation, sustained exposure is necessary for learners to translate this engagement into meaningful cognitive gains. As a caveat, exposure time and duration shall be managed accordingly in the integration of AR in the classroom. Excessive duration without proper scaffolding may lead to cognitive overload, while insufficient exposure may limit students' ability to engage deeply with the content and fully benefit from AR's interactive features. Therefore, educators should strike a balance by aligning AR intervention length with instructional goals, learner readiness, and the complexity of the subject matter (Simsek et al., 2025).

## Conclusions

This meta-analysis provides robust evidence that the integration of Augmented Reality (AR) in science education has a significantly positive effect on students' cognitive learning outcomes, with a large overall effect size (Hedges'  $g = 0.98$ , 95% CI [0.74, 1.21]). These outcomes include knowledge acquisition, conceptual understanding, academic performance, and higher-order thinking skills such as critical thinking and creative thinking. Despite the varied operational definitions of cognitive learning across disciplines, the included studies demonstrated methodological consistency in assessment, primarily using pre- and post-tests, which allowed for meaningful synthesis and comparison.

However, the analysis also revealed substantial heterogeneity ( $I^2 = 80.67\%$ ), prompting further investigation into potential moderators. The tested moderators were educational level, scientific discipline, and instructional duration. Only instructional duration significantly influences the effect size. Subgroup analysis showed that longer interventions (particularly those lasting 6–8 weeks) yielded higher effect sizes, indicating that sustained AR use enhances cognitive outcomes more effectively than shorter implementations. Furthermore, tests for publication bias (e.g., funnel plot symmetry, Egger's test, and fail-safe N calculations) indicated that the findings are generally robust and not unduly influenced by bias, though caution is warranted given the sensitivity of practical significance to a small number of unpublished studies.

Overall, the results underscore the practical value of integrating AR into science education, particularly when interventions are thoughtfully designed and implemented over

adequate time periods. Future research could focus on refining the measurement of cognitive outcomes, examining long-term learning effects, and expanding investigations to include diverse AR tools and educational contexts. Such efforts will help bridge the gap between technological innovation and effective pedagogy, ensuring that AR is leveraged not just as a novelty, but as a transformative tool in science education.

#### Abbreviations

AR: Augmented Reality; CI: Confidence Interval; SE: Standard error

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#### Author's contributions

Sarina Mae Barcenas- conceptualization, data analysis, data interpretation, writing

Maricar Prudente- supervision and mentoring for manuscript improvement

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#### Availability of data and materials

Not applicable

#### Declarations

#### Competing interests

The authors declare that they have no competing interests.

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