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Meta-analysis of the Impact of Aumented Reality on Motivation, Self-efficacy and Learning in Natural Sciences

Metaanálisis del impacto de la realidad aumentada en la motivación, la autoeficacia y en el aprendizaje en Ciencias Naturales

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ABSTRACT

Augmented reality is a valuable technology that integrates virtual elements with the real environment to create immersive and engaging learning experiences. Despite extensive literature on augmented reality in education, significant gaps remain regarding its specific impact on students' motivation and academic performance in Natural Sciences at the Primary Education level, and there is a lack of systematized pedagogical models guiding its implementation. This study addresses these gaps by analyzing the effect of augmented reality on motivation and academic outcomes and proposing a replicable pedagogical framework to guide its integration into teaching and learning processes. Furthermore, this work makes an interdisciplinary contribution, bridging educational practice and scientific understanding by simultaneously addressing variables related to motivation, didactics, and emerging technologies. For this purpose, a systematic review and meta-analytic methodology was employed, following PRISMA guidelines. The databases consulted were the Education Resources Information Center, Scopus, and Web of Science, from which a total of 57 documents were retrieved. After rigorously applying the established eligibility criteria, 4 studies were included in the systematic review and meta-analysis to ensure the validity and relevance of the findings. The meta-analytic results revealed an effect across the subgroups in favor of the experimental groups ($Z = 4.64$; $p < .00001$) and showed moderate heterogeneity across interventions ($I^2 = 0\%$). The findings highlight the potential of augmented reality to enhance students' motivation and engagement, improve academic performance, and provide practical guidance for teachers on effectively implementing augmented reality-based strategies. In conclusion, this study not only provides consolidated evidence on the benefits of augmented reality in Natural Sciences but also offers a structured pedagogical framework that can optimize teaching and learning, representing a novel contribution to educational practice and research.

RESUMEN

La realidad aumentada es una tecnología valiosa que integra elementos virtuales con el entorno real para crear experiencias de aprendizaje inmersivas y atractivas. A pesar de la extensa literatura sobre realidad aumentada en educación, existen lagunas significativas respecto a su impacto específico en la motivación y el rendimiento académico de los estudiantes en Ciencias Naturales a nivel de educación primaria, y falta de modelos pedagógicos sistematizados que guíen su implementación. Este estudio aborda estas lagunas analizando el efecto de la realidad aumentada sobre la motivación y los resultados académicos, y propone un marco pedagógico replicable para guiar su integración en los procesos de enseñanza y aprendizaje. Además, este trabajo realiza una contribución interdisciplinaria, vinculando la práctica educativa con la comprensión científica al abordar simultáneamente variables relacionadas con la motivación, la didáctica y las tecnologías emergentes. Para ello, se empleó una metodología de revisión sistemática y metaanálisis, siguiendo las directrices PRISMA. Las bases de datos consultadas fueron Education Resources Information Center, Scopus y Web of Science, de las cuales se recuperaron un total de 57 documentos. Tras aplicar rigurosamente los criterios de elegibilidad establecidos, se incluyeron 4 estudios en la revisión sistemática y el metaanálisis para garantizar la validez y relevancia de los hallazgos. Los resultados del metaanálisis mostraron un efecto a favor de los grupos experimentales ($Z = 4{,}64$; $p < .00001$) y una heterogeneidad moderada entre las intervenciones ($I^2 = 0\%$). Los hallazgos destacan el potencial de la realidad aumentada para mejorar la motivación y el compromiso de los estudiantes, incrementar el rendimiento académico y proporcionar orientación práctica a los docentes sobre la implementación efectiva de estrategias basadas en realidad aumentada. En conclusión, este estudio no solo proporciona evidencia consolidada sobre los beneficios de la realidad aumentada en Ciencias Naturales, sino que también ofrece un marco pedagógico estructurado que puede optimizar la enseñanza y el aprendizaje, representando una contribución novedosa a la práctica educativa y a la investigación.

KEYWORDS | PALABRAS CLAVE

Natural Sciences, Meta-analysis, Motivation, Augmented Reality, Systematic Review, Academic Performance.
Ciencias naturales, metaanálisis, motivación, realidad aumentada, revisión sistemática, rendimiento académico.

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1. Introduction

1.1. Historical Background

Currently, the social and educational spheres are undergoing profound transformations (Ho et al., 2023). Information and communication technologies (ICT) have redefined educational processes, promoting more active, innovative, and student-centered learning environments (Garzón & Inga, 2023). These tools facilitate interaction and collaboration between teachers and students, enabling more dynamic methodologies tailored to individual needs (Shakirova et al., 2024), while education is conceived as a space where creativity and participation are essential for the holistic development of the student (Sáez-López et al., 2020). In this context, educational institutions must update their pedagogical approaches, moving toward models that foster competency-based learning and active participation in society (Pavlou & Castro-Varela, 2024). This entails strengthening students' digital skills and leveraging ICT to energize the teaching-learning process (Erbas & Demirer, 2019). Furthermore, the modernization of educational resources makes content more accessible and engaging, stimulating curiosity and interest in learning (Lampropoulos & Kinshuk, 2024; Moreno-Guerrero et al., 2020).

In our contemporary digital era, the deep integration of the Internet, mobile devices, and innovative educational technologies has revolutionized the landscape of digital education. This transformation has opened a world of possibilities, enriched by the versatility and accessibility of digital learning, which transcends temporal and spatial boundaries (Chen et al., 2025). In this context, augmented reality (AR) has established itself as an educational tool capable of creating immersive learning experiences through mobile devices (Buchner & Kerres, 2021). It promotes meaningful, contextualized, and interactive learning (Simón-Sánchez & Fernández-Sánchez, 2023). Although its development began in the 1990s, its use has grown recently due to reduced costs and increased technological accessibility (Osborne & Mavers, 2019). AR combines virtual elements with the physical environment, enhancing the user's visual perception through real-time graphics (Sahin & Yilmaz, 2020), which in education can increase student engagement and improve academic performance. It is crucial to differentiate AR from virtual reality (VR): AR overlays digital content onto the real world, whereas VR creates fully virtual environments that are difficult to replicate physically (Lytvynova & Soroko, 2023). Key features of AR include the fusion of physical and virtual environments in three dimensions, the generation of 3D experiences, and real-time interaction with digital elements (Danakorn Nincarean et al., 2019). Both technologies can enrich education when implemented in alignment with pedagogical objectives (Rueda Márquez de la Plata et al., 2023).

1.2. Theoretical Framework

From Bandura's perspective, self-efficacy has become a key construct for explaining both human behavior and academic performance (Bandura, 1986). Motivation, particularly intrinsic motivation, plays a central role in initiating and sustaining learning processes while enhancing the perception of self-efficacy, understood as the personal conviction regarding one's ability to handle academic tasks (Bandura, 2000). This efficacy judgment directly influences the choice of activities, as well as the level of effort and persistence in the face of challenges (Honicke & Broadbent, 2016). More recent research shows that motivation promotes the use of metacognitive and self-regulation strategies, indirectly contributing to better academic performance through strengthened self-efficacy (Uchida et al., 2018). Consequently, fostering both motivation and self-efficacy is considered an essential strategy for achieving sustainable academic success (Fu et al., 2025). For instance, Soriano-Sánchez and Jiménez-Vázquez (2023) highlighted the influence of these factors in higher education fields such as education sciences, engineering and architecture, health sciences, and the arts and humanities. AR can enhance motivation and self-efficacy by representing complex phenomena in a visual and interactive manner, facilitating the understanding of abstract concepts in Natural Sciences, such as biological, chemical, or physical processes (O'Connor & Mahony, 2023). It allows students to interact with, observe, and manipulate virtual environments that simulate reality, promoting deep, meaningful, and contextualized learning (Ciloglu & Ustun, 2023). In this way, AR reinforces motivation, engagement, and self-efficacy, indirectly contributing to academic performance. Other studies have reported AR's effectiveness in improving learning outcomes related to the states of water in students with intellectual disabilities (Iatraki & Mikropoulos, 2025).

However, its implementation presents challenges. Technical limitations, lack of clear guidelines, or the need for prior knowledge can hinder its use (Barroso-Osuna et al., 2019). Nevertheless, when applied appropriately, AR generates positive experiences, increases motivation, and can improve academic outcomes (Redondo et al., 2020). Motivation enhances participation, collaboration, interest, attention, and student satisfaction (Bölek et al., 2021). According to Keller (1983) motivation depends on internal and external factors that condition students' active engagement in learning.

The literature on the impact of ICT in education is extensive (Sijimol, 2024), although studies specifically focused on AR remain limited. Soriano-Sánchez and Jiménez-Vázquez (2023) emphasize its potential to stimulate cognitive skills, promote inclusion, and improve motivation and academic performance, highlighting the need to investigate its application across different educational levels and contexts (Ábalos-Aguilera et al., 2024). AR facilitates more dynamic and interactive learning, supporting knowledge retention and the development of specific competencies (Hönemann et al., 2025).

1.3. Justification of the Present Study

AR offers numerous benefits for teachers and the wider educational community, fostering active participation, enhancing comprehension of abstract concepts through 3D representations, increasing motivation with engaging visual resources, and adapting teaching to diverse learning styles (Aygün & Çelik, 2024; Flores-Bascuñana et al., 2020; McBain et al., 2022). It also promotes collaboration, social skills, digital competencies (Amirbekova et al., 2024), critical and creative thinking (Ozdamli & Hursen, 2017), risk-free practical experiences (Tarng et al., 2018), and educational inclusion.

From a methodological perspective, this study addresses a clear gap in literature: although research exists on educational technologies and meta-analyses related to ICT in Natural Sciences, the effect of AR on motivation and academic performance in Primary Education has not been systematically explored. Traditional teaching methods often struggle to convey abstract concepts and foster active participation. By adopting an interdisciplinary approach that integrates educational psychology (motivation and self-efficacy), science education, and emerging technologies, this study provides consolidated evidence and practical strategies to optimize teaching and learning in Natural Sciences.

This research builds on recent meta-analyses that demonstrate AR's positive impact in educational settings. For example, Na and Yun (2024) found a significant positive effect of AR on K-12 students' motivation ($g = 0.803$), while Adi et al. (2025) reported substantial improvements in academic performance. By integrating AR into a replicable pedagogical framework, this study not only enhances motivation and academic outcomes but also supports student engagement, collaboration, and the development of digital competencies, offering teachers practical guidance to optimize learning processes in primary-level Natural Sciences.

1.4. Current State of the Art

To validate these benefits, meta-analyses are essential, as they allow the integration and comparison of results from multiple studies, providing a solid level of evidence to guide future research and optimize pedagogical practices (Myung, 2023). Although some meta-analyses exist on AR and student motivation, its specific influence on motivation to learn Natural Sciences has not yet been explored through systematic review and meta-analysis. In the science curriculum, AR helps in understanding abstract concepts or non-observable phenomena and better explaining scientific knowledge by overlaying virtual objects onto real environments (Xu et al., 2022). Its capacity to increase motivation and engagement (Bölek et al., 2021; Redondo et al., 2020) makes it a key resource for active, student-centered teaching strategies. Despite these advances, there is still a lack of meta-analytic studies evaluating its impact on motivation and learning in Natural Sciences at the Primary Education level, highlighting the need to systematically explore these effects and provide evidence-based guidance for educational practice (Fu et al., 2025). In this context, the choice of Natural Sciences as a study area is justified by the relevance of this discipline for students' comprehensive development and the complexity of its content, which often hinders understanding and reduces motivation. This field offers an ideal context to assess the impact of innovative tools, such as AR, on motivation, engagement, and academic performance, enabling the development of more effective, student-centered pedagogical strategies.

1.5. The Present Study

Based on the above, although meta-analyses have examined the impact of ICT on Natural Sciences to address diversity and individual differences (Soriano-Sánchez, 2025), to date, no studies have specifically analyzed the influence of AR on motivation in learning Natural Sciences. In the context of technological advancement, AR emerges as a highly promising tool for optimizing teaching and learning processes.

Therefore, the objective of this study is to analyze the effect of AR on students' motivation and academic performance in the area of Natural Sciences.

Despite the growing literature on AR in education, significant gaps remain there is no consolidated evidence regarding its specific effect on motivation and academic performance in Natural Sciences at the Primary Education level, nor are there systematized models guiding its didactic implementation. This highlights the need to identify effective pedagogical strategies, optimize their application, and evaluate their impact to provide a replicable framework that enhances teaching and learning processes through AR.

As operational tools to achieve these objectives, the study proposes a pedagogical application framework based on AR, which combines innovative didactic interventions, integration of AR into learning activities, and evaluation of its impact on motivation and academic performance. This approach provides a practical and replicable guide for teachers, aimed at optimizing teaching and learning processes, enhancing the understanding of abstract concepts, and fostering student motivation and engagement.

To address these gaps and guide the investigation, the study poses the following research questions:

1. How does AR influence students' motivation to learn Natural Sciences at the Primary Education level?
2. What effect does the use of AR have on students' academic performance in Natural Sciences?
3. Which pedagogical strategies and AR-based application models are most effective for optimizing the teaching and learning of abstract concepts in Natural Sciences?
4. How can AR be systematically integrated into educational activities to ensure replicable improvements in motivation and academic performance?

Based on the review of previous studies, the following hypotheses (H) are proposed:

H.1: Students who use AR exhibit significantly higher levels of motivation compared to those who do not use this technology.

H.2: The greater the exposure or intervention time with AR, the better the learning outcomes achieved by students.

In addition, the present study makes a novel contribution: Although there is extensive literature on AR in education, few studies have specifically examined its effect on motivation and academic performance in Natural Sciences at the Primary Education level, and systematized models guiding its didactic implementation are lacking. This study combines an innovative pedagogical approach with a systematic review and meta-analysis, identifying effective AR integration strategies, evaluating their impact on motivation and academic achievement, and proposing a replicable framework for application in educational contexts. Thus, the study not only provides consolidated evidence on the effects of AR but also offers practical tools for teachers and educational stakeholders, optimizing teaching and learning processes and enhancing the understanding of abstract concepts in Natural Sciences.This research thus represents a novel interdisciplinary contribution, combining insights from educational psychology, science didactics, and emerging technologies to enhance teaching and learning in Natural Sciences.

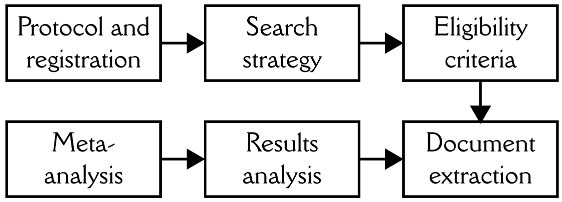
2. Methodology

2.1. Information Sources and Search Strategy

This research was based on a systematic review of scientific literature. The study followed the guidelines proposed by the PRISMA statement (Page et al., 2021) (Figure 1).

The search was conducted in September 2025 in the following databases: Education Resources Information Center (ERIC), Web of Science (WoS), and Scopus, using the "All Fields" option. Filters were applied for studies published in English and Spanish. The search query used was as follows: ((*"augmented reality"*) AND (*"motivation"* OR *"self-efficacy"* OR *"academic performance"*) AND (*"Natural Sciences"*)). The results obtained from each of the databases were as follows: 11 in ERIC, 17 in WoS, and 29 in Scopus.

Figure 1: Synthesis of the Steps Involved in Conducting A Systematic Review with Meta-analysis (PRISMA statement).



2.2. Inclusion and Exclusion Criteria

Regarding the inclusion criteria, they were as follows: a) Empirical studies without limitation on the publication date; b) Research including the treatment of two comparable groups; c) The variable to be measured was motivation related to the use of AR in the learning of Natural Sciences at any educational level; and d) Articles published in peer-reviewed journals.

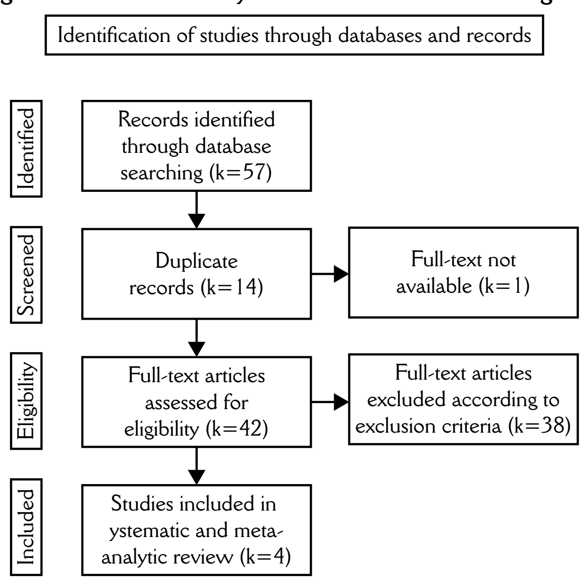
On the other hand, the exclusion criteria were: a) Restricted access to the publication; b) Duplicate studies; c) Conference proceedings, doctoral theses, book chapters, or books; d) Theoretical research, reviews, case studies, or cross-sectional studies; e) Not relevant to the study topic; and f) Lack of data for meta-analysis.

2.3. Data Selection and Collection Procedure

The two researchers (JGSS and DJV) independently reviewed the titles and abstracts of the identified records. They retrieved and fully read the preselected records. In cases of disagreement, a thorough reading of the full text was conducted to apply the remaining conceptual and methodological criteria. Information from the records that met the eligibility criteria was extracted into a database.

The search strategy used yielded a total of 57 documents, of which 52 were excluded based on the established exclusion criteria. The exclusions were as follows: 1 restricted-access study, 14 studies that did not meet criterion b, 5 studies under criterion c, 13 studies under criterion d, 19 studies that met criterion e, and 1 study under exclusion criterion f. Accordingly, the flow diagram illustrates the process followed and the screening of scientific articles, leading to the final sample (Figure 2). Finally, 4 studies met the eligibility criteria and were included for review and meta-analysis.

Figure 2: Screening of Articles for the Systematic Review According to the PRISMA Flow.



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2.4. Data Extraction

For data extraction, a form was designed that included information based on the established inclusion criteria. First, the information was coded following this process: (1) authors, (2) year of publication, and (3) study objective. Subsequently, a second questionnaire was completed, including: (1) study, (2) language of publication, (3) location, (4) study design, (5) participants in each group, and (6) age range/mean age. Finally, the information was coded for: (7) study, (8) educational stage, (9) variables analyzed, (10) instruments used, and (11) mode of intervention. Using these tools, the most relevant qualitative and quantitative data from each study were extracted. This process was carried out by both authors (JGSS and DJV) to ensure maximum reliability in data collection and to resolve discrepancies through a second reading of the documents.

2.5. Data Analysis: Meta-analysis

First, the intervention review option was selected to test the efficacy of the interventions, following a random-effects model. The meta-analysis was conducted using the statistical software Cochrane Review Manager (RevMan), version 5.4 (Cochrane, London, UK), to assess study heterogeneity, effect size, data quality, etc. (Sánchez-Meca & Ato, 1989), providing a high level of evidence on the efficacy of the interventions. Effect sizes were considered favorable if the results indicated improvement across interventions, statistical significance was assessed using the p-value, and the overall efficacy was considered significant if $p < 0.05$. Study heterogeneity, on the other hand, examined the extent to which results from different studies could be combined into a single measure. Differences in study design, population characteristics, and other factors could lead to varying results. Heterogeneity was considered high if $I^2 \geq 75\%$, moderate if 50–75%, and low if $I^2 \leq 25\%$ (Higgins et al., 2003).

2.6. Data Analysis: Meta-analysis

The risk of bias was assessed by examining the distribution of points in the funnel plot, following the guidelines suggested by Higgins et al. (2011). Thus, the two researchers independently evaluated the risk of bias, resolving any disagreements through a consensus meeting.

2.7. Protocol Registration

The protocol for this review was registered in PROSPERO (CRD420251142675), ensuring transparency and traceability of the review process in accordance with the best practices recommended by PRISMA. This registration allowed the public documentation of the objectives, methods, and planned analyses prior to conducting the study.

2.8. Keyword Co-occurrence Analysis

To analyze the co-occurrence of keywords retrieved from the literature search, an automated analysis was conducted using VOSviewer, a software tool specialized in constructing and visualizing bibliometric networks (Van Eck & Waltman, 2010).

3. Results

The search strategy and the established inclusion and exclusion criteria yielded a total of 4 studies for systematic and meta-analytic review. The most relevant qualitative results of the research are presented below.

3.1. Aanalysis of the Selected Studies

First, regarding the year of publication, two studies were conducted in 2014 (Chiang et al., 2014), one in 2016 (Chen et al., 2016), one in 2022 (Cai et al., 2022), and one in 2024 (Chen et al., 2024), reflecting a growing interest in this field of study. With respect to the research objective, all studies shared the goal of evaluating the potential of AR in students' motivation and/or academic performance (Table 1).

Table 1: Authors, Year of Publication, and Objectives of the Included Studies.		
Authors	Year of publication	Study objective
Cai et al.	2022	To explore the impact of an AR-based scientific inquiry tool based on a brain-computer interface (BCI) on primary school students' scientific performance, flow experience, self-efficacy, and cognitive load
Chen et al.	2016	To evaluate whether the use of the CMAR system improves students' learning, motivation, and attitude compared to a conventional AR system
Chen et al.	2024	To enhance students' motivation, interest, and learning outcomes through the use of AR combined with mobile learning, while introducing the concept of auroras in the context of climate science to promote environmental awareness
Chian et al.	2014	To propose an AR-based mobile learning system for conducting inquiry-based learning activities and examine the effectiveness of the approach in terms of learning achievements and motivation

Note. AR = Augmented Reality; CMAR = Concept-Mapped Augmented Reality.

All the studies (k = 4) were published in English (Cai et al., 2022; Chen et al., 2024; Chiang et al., 2014). Three of them were conducted in Taiwan (Cai et al., 2022; Chen et al., 2024), while one was carried out in China (Cai et al., 2022). Regarding the study design, all employed a quasi-experimental approach. As for the sample size, it ranged from 21 participants in the experimental group and 20 in the control group (Cai et al., 2022) to 36 participants in the experimental group and 35 in the control group (Chen et al., 2016), with ages ranging from 9–10 years (Chiang et al., 2014) to 11–12 years (Chen et al., 2024) (Table 2).

Table 2: Study, Language of Publication, Location, Study Design, Participants, and Ages.					
Study	Language of Publication	Location	Study Design	Participants in each Group (***n***)	Age Range / Mean Age
Cai et al. (2022)	English	China	Quasi-experimental	41 (EG = 21; GC = 20)	10–13 years old
Chen et al. (2016)	English	Taiwan	Quasi-experimental	71 (EG = 36; GC = 35)	10–11 years old
Chen et al. (2024)	English	Taiwan	Quasi-experimental	48 (EG = 24; GC = 24)	11–12 years old
Chian et al.(2014)	English	Taiwan	Experimental	57 (EG = 28; GC = 29)	9–10 years old

Note. EG = Experimental Group; CG = Control Group.

Regarding the educational stage, all studies were conducted at the Primary Education level (Cai et al., 2022; Chen et al., 2016; Chen et al., 2024; Chiang et al., 2014), evaluating academic performance, self-efficacy, and/or cognitive load as indicators of learning achievement. For this purpose, various instruments were employed, including the *Self-efficacy Scale* (Ibrahim et al., 2016), which is related to motivation, among others (Table 3). The duration of the interventions ranged from a single session of one and a half hours (Cai et al., 2022) to 18 weeks, with two or three weekly sessions of 45 minutes each. All interventions were conducted face-to-face.

Table 3: Study, Educational Stage, Variables Analyzed, Instruments Used, Intervention Time, and Mode of Intervention.					
Study	Educational Stage	Variables Analyzed	Instruments used (motivation and/or academic performance)	Treatment and Intervention Duration	Mode of Intervention
Cai et al. (2022)	Primary Education	Academic performance, self-efficacy, and cognitive load	B	1 hour 35 minutes	In-person
Chen et al. (2016)	Primary Education	Attitude toward learning and motivation	A and C	4 hours and 20 minutes	In-person
Chen et al. (2024)	Primary Education	Motivation and learning outcomes	A	18 weeks (two or three weekly sessions of 45 minutes each)	In-person
Chian et al. (2014)	Primary Education	Learning Achievement and Motivation	D	6 hours	In-person

Note. A = Instructional Materials Motivation Survey (Keller, 2010); B = Self-efficacy (Ibrahim et al., 2016); C = Learning Attitude Questionnaire (Hwang et al., 2013); D = Cognitive Load Survey (Sweller et al., 1998).

3.2. Synthesis of the Evidence Found

In Primary Education, various AR interventions demonstrated improvements in both student learning and motivation. Chen et al. (2024) conducted a scientific inquiry experiment on the lever principle, comparing an experimental group that used a BCI-based AR system with attention feedback, and a control group that used simple AR. Students in the EG maintained higher levels of concentration and flow, significantly improving their performance and confidence in scientific inquiry, particularly in conducting surveys, which showed that BCI-enhanced AR strengthened self-efficacy in inquiry tasks (Cai et al., 2022).

Additionally, the Aurora AR System application in group mobile learning facilitated the understanding of complex phenomena, such as auroras, within the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach, promoting interest, active participation, and motivation among sixth-grade students. Similarly, Chen et al. (2016) found that the CMAR system facilitated the comprehension of abstract concepts and knowledge organization through the integration of 3D models, animations, and interactive concept maps, enhancing academic performance, attitudes toward learning, and motivation, with notable increases in attention, relevance, confidence, and satisfaction.

Furthermore, mobile AR-based learning about aquatic animals and plants allowed students to explore objects immersively, receive contextualized guidance, and access relevant materials, which increased their motivation, attention, and satisfaction without increasing cognitive load and supported more efficient content processing (Cai et al., 2022; Chiang et al., 2014). Overall, these findings indicated that AR—whether in mobile form, integrated with BCI, or combined with concept-mapping systems—enhanced student learning, motivation, self-efficacy, and active participation, facilitating the understanding of complex concepts and the completion of scientific inquiry tasks.

3.3. Summary of Meta-analytic Results

The meta-analytic findings on the use of AR in student motivation and learning (k = 4) included a total of 109 participants in the experimental group and 108 in the control group (Figure 3). The results indicated low heterogeneity regarding the differences in the interventions (I^2 = 0%), with a standardized mean difference (SMD) of 7.12, at a 95% confidence interval (CI) [4.11, 10.13], and the effect of the interventions was significant (Z = 4.64; p < .00001).

In interpreting the meta-analysis, the symbols are defined as follows:

■ Green squares: represent the effect size (mean difference) of each individual study. The size of the square reflects the weight of the study in the meta-analysis.

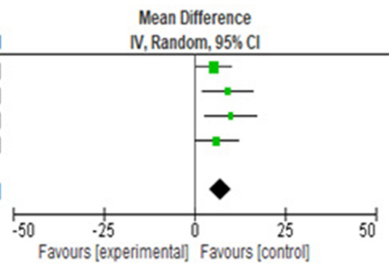
— Black horizontal lines that cross the squares represent the 95% CI for each study.

◆ The black diamond at the bottom of the plot illustrates the overall combined effect across all studies, with its width reflecting the 95% CI for this aggregated effect.

Figure 3: Forest Plot of the Overall Effect Size of the Interventions.

	Experimental			Control				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Cai et al. (2022)	79.19	6.5	21	73.8	9.12	20	38.2%	5.39 [0.52, 10.26]
Chen et al. (2016)	71.89	14.56	36	62.69	15.23	35	18.9%	9.20 [2.27, 16.13]
Chen et al. (2024)	81.34	10.36	24	71.25	14.83	24	17.3%	10.09 [2.85, 17.33]
Chiang et al. (2014)	80.1	8.76	28	73.93	13.7	29	25.6%	6.17 [0.22, 12.12]
Total (95% CI)			**109**			**108**	**100.0%**	**7.12 [4.11, 10.13]**

Heterogeneity: Tau² = 0.00; Chi² = 1.58, df = 3 (P = 0.66); I² = 0%
Test for overall effect: Z = 4.64 (P < 0.00001)

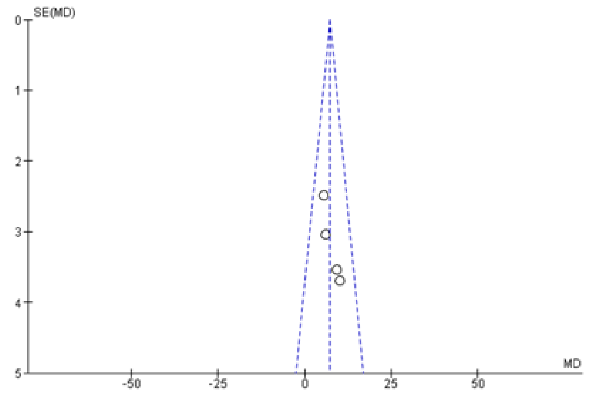


Note. Tau² = estimate of the variance of effect sizes; Chi² = presence of heterogeneity; I² = percentage of heterogeneity across the interventions; Z = effect size; df = overall indicator of the effect size in the meta-analysis; p = statistically significant heterogeneity; green dots = effect size of each study; black diamond for each variable = effect size of the set of studies; final black diamond = subgroup effect size.

3.4. Risk of bias of the Included Studies

Once the studies for the meta-analysis were selected, the reliability of the results was assessed by evaluating the risk of bias using the Cochrane tool. The funnel plot (a graph that checks for publication bias) was used. This allowed for observing the risk of bias results in students' motivation and academic performance in relation to the use of AR (Figure 4). For interpretation, a clustering close to the vertical line of the graph with respect to the different points is associated with a low risk of bias.

Figure 4: Overall Risk of Bias.



In summary, the inspection of the point distribution allowed verification that there was no risk of bias in any of the components analyzed in this study, with respect to the studies included in the meta-analysis and the set of interventions.

3.5. Keyword Co-occurrence Analysis

Figure 5 corresponds to a conceptual map or semantic network that shows the relationship between different concepts related to the teaching of Natural Sciences and the use of AR. At the center are two main nodes: "AR" and "natural science." Both act as axes connecting to the other elements.

On the left side appears the term "influence", which connects to both AR and Natural Sciences, suggesting that both dimensions are affected by external factors while also influencing other processes.

On the far right are two pedagogical concepts: "didactic strategy" and "potentialization/empowerment". These link directly to the central nodes, reflecting how AR and Natural Sciences can be integrated as teaching strategies and as means to enhance and empower learning.

In visual terms, colors also convey differentiation:

- Red/pink links represent the connections between influence, AR, and Natural Sciences.
- Green links indicate the relationship toward didactic strategies and empowerment.
- In the center, more neutral tones show the intersection of both fields, highlighting the role of AR as a mediator between science and pedagogy.

Figure 5: Thematic or Cluster Node Map.

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The network shows that AR not only influences the teaching of Natural Sciences but also emerges as an innovative didactic strategy, capable of enhancing and empowering learning, positioning it as a bridge between the scientific and pedagogical dimensions.

4. Disccusion and Conclusions

4.1. Discussion of Results

The results of this study allow us to confirm the proposed objective, which was to analyze the effect of AR on students' motivation and academic performance in Natural Sciences In this regard, consistent with the proposed pedagogical application framework, AR appears to enhance motivation by offering interactive and visual experiences that make content more engaging, facilitates the understanding of abstract and non-observable concepts through 3D visualizations and real-world scenario simulations, and promotes collaboration, student participation, and the development of digital competencies (Campos-Mesa et al., 2022; Rueda Márquez de la Plata et al., 2023).

Addressing the first research question and hypothesis, the findings indicate that students using AR exhibit significantly higher levels of motivation compared to those who do not use this technology. This effect may be due to interactive and visual experiences, real-world scenario simulations, and 3D models that facilitate the understanding of abstract concepts and foster active participation (Chin et al., 2019; Dutta et al., 2023; Henssen et al., 2020; Lytvynova & Soroko, 2023). In relation to the second research question and hypothesis, the study confirms that greater exposure or longer intervention time with AR leads to improved academic outcomes in Natural Sciences, demonstrating that AR not only increases motivation but also enhances performance through the strengthening of self-efficacy, meaningful learning, and retention of complex content (Bölek et al., 2021).

To address the third research question, the findings suggest that the most effective pedagogical strategies include the integration of AR in collaborative activities, the use of 3D models, interactive animations, and concept-mapping systems within a planned and replicable instructional framework. This approach could constitute a systematic model that optimizes the teaching of abstract concepts in primary-level Natural Sciences. Implementation criteria for these findings include structured activity planning, integration of 3D models and interactive tools, and continuous evaluation of motivation and academic performance. Its potential impact extends to the fields of education and media, enhancing digital literacy, visual communication, and the understanding of complex concepts. Teachers are recommended to apply these strategies systematically, fostering active participation and meaningful learning. By integrating AR within a systematic instructional framework, the technology is suggested to create a dynamic learning environment that increases participation, interest, and motivation, which in turn improves attention, cooperation, satisfaction, and ultimately academic performance (Bölek et al., 2021; Lampropoulos & Kinshuk, 2024). These outcomes align with the study's aim to provide evidence-based guidance for optimizing teaching and learning processes and demonstrate the effectiveness of AR-based pedagogical strategies for Primary Education in Natural Sciences. Furthermore, the findings support competency-based learning by promoting skills necessary for active participation in society, linking the study's results to broader educational goals, including the Sustainable Development Goals.

The findings indicate that research on educational technology has primarily focused on variables such as academic achievement, motivation, and attitude, consistent with the close relationship among these dimensions. Additionally, the prevalence of mobile applications and paper marker-based materials as AR resources reflects a preference for accessible and easily implemented tools (Arici et al., 2019). However, AR only enhances science teaching if it is integrated within a properly planned instructional framework (Penn, 2022). These findings support the hypothesis that students using AR exhibit significantly higher levels of motivation than those who do not use this technology. Studies such as Chen et al. (2024) show that a BCI-based AR system with attention feedback increases concentration, flow, and self-efficacy in inquiry tasks compared to simple AR (Cai et al., 2022). Similarly, Aurora AR System and CMAR facilitate the understanding of complex concepts through 3D models, animations, and interactive maps, promoting interest, participation, and academic performance (Chen et al., 2016; Chiang et al., 2014). Altogether, these results confirm that AR—whether mobile, integrated with BCI, or combined with concept-mapping systems—enhances motivation, self-efficacy, and active participation among students. These findings reinforce the evidence on the benefits of AR, providing clear criteria for its implementation and practical suggestions for its use in educational and media contexts.

The choice of Natural Sciences as the area of study is justified by its relevance in the comprehensive development of students and the complexity of its content, which often hinders understanding and reduces motivation. The results of this study confirm that AR significantly increases motivation and improves academic performance in this field, demonstrating that its integration within a systematic and replicable pedagogical framework optimizes teaching and learning processes. Additionally, effective strategies were identified, such as the use of 3D models, interactive animations, and collaborative activities, which allow abstract and non-observable concepts to be taught in a more understandable and engaging way. These findings highlight the relevance of implementing AR in Natural Sciences, offering consolidated evidence, practical tools for teachers, and a pedagogical framework that strengthens student motivation, engagement, and digital competencies.

The meta-analysis reinforces these findings, showing that AR generates higher motivation and academic performance in Natural Sciences compared to traditional methods, and that the duration of the intervention does not significantly affect the studied variable. This aligns with previous studies suggesting that even brief interventions can be effective (Soriano-Sánchez & Jiménez Vázquez, 2025). Low heterogeneity and the absence of risk of bias confirm the consistency and reliability of these effects across different studies. Various AR systems, including mobile applications, BCI-integrated platforms, and concept-mapping tools, support student engagement, self-efficacy, and active participation, validating the operational tools proposed within the pedagogical framework.

Regarding the fourth research question, the results indicate that the systematic integration of AR into educational activities ensures replicable improvements in motivation and academic performance, provided it is combined with a clear pedagogical framework, structured instructional planning, and continuous assessment. The consistency and replicability of these effects depend on the correct implementation of AR-based strategies and the ongoing monitoring of outcomes over time. Furthermore, recent studies emphasize the importance of systematically applying innovative AR-based pedagogical strategies to promote competency-based learning in Natural Sciences content (Soriano-Sánchez et al., 2025).

The keyword co-occurrence analysis has shown that AR and Natural Sciences are central nodes connecting key concepts. The node "influence" reflects reciprocal effects in both fields, while "didactic strategy" and "potentialization/empowerment" highlight how AR can enhance and strengthen learning. The network confirms that AR acts as a bridge between scientific content and pedagogical innovation, positioning it as an effective strategy to increase motivation, engagement, and academic outcomes.

Nevertheless, the study presents some limitations, such as the restricted selection of databases (ERIC, WoS, and Scopus), the number of included articles, and sample size, as well as limited evidence in educational levels other than Primary Education. Despite this, and notwithstanding the limited number of studies available in this line of research, a notable strength of the present study is the relevance of using augmented reality in Primary Education to enhance student motivation and improve academic performance in Natural Sciences content. On the other hand, from a practical perspective, AR can also be applied in higher education and other contexts through interactive simulations, immersive 3D experiences, and gamified learning, reinforcing the proposed replicable pedagogical framework. Likewise, it would be valuable to implement this methodological strategy in initial teacher education, so that future teachers acquire the necessary competencies to ensure quality education, promoting students' understanding and interpretation of the physical and natural environment in a more meaningful and comprehensive way, in line with societal demands and the principles of STEAM education, fostering creativity, critical thinking, and problem-solving skills.

Future studies should explore these possibilities using standardized assessment instruments to reduce bias and further validate the impact of AR on motivation and academic performance across different educational levels. Finally, it is recommended that future research explore the impact of AR on motivation and academic performance at other educational levels, such as Early Childhood, Secondary, and Higher Education, and use standardized assessment instruments to reduce the risk of bias. Likewise, it is recommended that future research continue evaluating the impact of AR in interdisciplinary contexts, measuring both cognitive and socio-emotional effects, and generating practical guidelines that can be applied in educational and media environments.

4.2. Conclusions

This study highlights the positive effect of AR on student motivation and academic performance in Natural Sciences. The findings show that AR enhances motivation, facilitates the understanding of abstract and non-observable concepts, increases student participation and engagement, and contributes to improved academic performance. AR applications improve pedagogical strategies, spark interest in learning, and significantly enhance students' knowledge. Therefore, their implementation is recommended in both face-to-face and online settings, as they provide a personalized pedagogical approach, optimize teaching and learning processes, and ensure educational quality.

The meta-analysis findings show that AR is an effective tool for enhancing motivation, content acquisition, and academic performance, even with a single session. Additionally, it supports the development of media literacy and social, cognitive, and emotional skills, making it advisable to integrate AR systematically in higher education, leveraging its interactivity and ability to stimulate student engagement. This highlights the need to systematically integrate AR across different educational levels, leveraging its interactivity and ability to stimulate active student participation.

This analysis underscores AR's pivotal role as both a mediator and enhancer in science education, linking content mastery with innovative pedagogical practices.

Among the study's limitations are the restricted selection of databases (ERIC, WoS, Scopus), the number of articles analyzed, the sample size, and the limited evidence at educational levels other than Primary Education.

Finally, this work opens opportunities to further investigate motivation and academic performance in Natural Sciences across different educational levels, strengthening this research line and contributing to quality education.

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