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**Review Article**

# Augmented Reality in Natural Sciences and Biology Teaching: Systematic Literature Review and Meta-Analysis

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**Abstract**

This article presents the results of a systematic literature review followed by a meta-analysis of studies on the use of Augmented Reality (AR) in the teaching and learning of Natural Sciences and Biology, among primary and secondary school students. The variables considered were the effects on student learning and motivation, as well as other variables like students understanding and students' perception of the cognitive load. The teaching contexts and strategies used in association with AR were also considered. The PRISMA methodology was used in articles published between 2010 and 2023, in EBSCO, Science Direct, Scopus, Springer Link, Taylor & Francis and Web of Science databases. Seven hundred and twenty-one articles (721) were found, which, after applying the inclusion and exclusion criteria, were reduced to 15. The results showed that, in most studies, AR associated with certain teaching strategies and using a quasi-experimental research methodology produced better results in learning and student motivation and other variables such as student understanding and memorization (from Bloom's taxonomy), and perception of cognitive load. The overall analysis of the data allowed us to observe a strong effect size value ($d$ = 1.13 [0.39;1.86]) in favour of the experimental group regarding learning and a moderate effect on motivation when using AR ($d$ = 0.52 [0.30;0.74]). The same occurred with other variables studied where students obtained better results, which translated into a small or medium effect size. For example, in the perception of cognitive load, the effect size was $d$ = 0.73.

**Keywords:**

Augmented Reality;
Biology Teaching;
Meta-analysis;
Science Education;
Science Teaching.

**Article History:**

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## 1- Introduction

This article presents the results of a systematic literature review (SLR) and meta-analysis on the use of Augmented Reality (AR) in the process of teaching of Natural Sciences (NS) and Biology to students of primary and secondary education. AR has been gradually integrated into research in non-higher levels of education. Despite the positive results evidenced by research [1-6], AR has rarely been included in formal learning contexts, although there is considerable investment in AR applications and resources. Data from the Statista portal (2023) indicates a worldwide growth between 2016 and 2022, from 1031.10 to 6059.80 million augmented reality applications. The authors Weng et al. (2020) [7] state that the disappearance of printed schoolbooks is not imminent, and they are in favor of a review of their structure with the integration of AR instead of just being replaced by the digital book version, which can cause high visual fatigue. There has also been a growth in accessible devices that allow running AR applications [8], called Mobile Augmented Reality (MAR) [9], such as smartphones, tablets, Personal Digital Assistants (PDA), portable game consoles, or even visual systems such as glasses. Due to different designations between countries to name the various school cycles, it was our option to use the International Standard Classification of Education, i.e., ISCED [10, 11], given its global acceptance. In this article, ISCED levels 1 to 3 were considered, which led to the exclusion of students from higher education. The ISCED levels 1 to 3 classification corresponds to students ages between 5 to 18 years old, being equivalent, in some

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education systems, to the designations primary (Elementary school/École élémentaire), lower secondary (Middle school/Collége), and upper secondary (High school/Academic), expressions found in the studies analysed and that we also chose to include in this article. The question that can be asked is: Why use AR in learning NS and Biology with primary and secondary school students? One answer may be to increase the level of scientific literacy of students aged 5 to 18. But there are more reasons that we will present throughout this SLR and meta-analysis. According to Cavagnetto (2010), "scientific literacy is the ability to accurately and effectively interpret and construct science-based ideas in the popular media and everyday contexts" [12]. The teaching of NS and Biology implies an adequate use of educational resources that favour the correct learning and appropriation of knowledge associated with these disciplines without biasing the rigor accepted by the scientific community or the establishment of alternative conceptions [2, 8, 13–15].

Certain AR applications allow us to achieve these goals. Associated with learning Liu et al. 2023 [5] state, "AR contains three characteristics of virtual and real combination, real-time interaction, and 3D registration, which can add objects to the real environment to enhance the user's perception of the real world and interaction with the real world." (p.195). According to Mladenovic (2020) [16], AR is a three-dimensional simulation environment created using software and hardware to provide the user with a realistic interaction experience. Chang et al. (2016) [13], as well as Akçayır & Akçayır (2017) [17] and Pedaste et al. (2020) [18] cite several authors, refer to the superimposition of virtual objects on physical objects, allowing the visualization of phenomena or abstract structures and concepts not observable to the naked eye and also of natural processes that would be too slow to observe taking into account their cycles of life. Alkhasawneh & Khasawneh (2024) [19] express that the basis of AR technology is the creation of a link between real physical features and equivalent virtual elements, and, by merging the physical and virtual worlds, AR offers the potential to close the gap between academic and applied education. Wang et al. (2022) [15] emphasize the use of AR to observe microscopic, abstract, and non-visible aspects, stating that in this way it can support the learning and performance of students with more difficulties with spatial thinking. This use of AR can be seen concomitantly with the importance of carrying out practical laboratory activities mentioned by Hofstein & Lunetta (1982) [20], as it makes it possible to experience phenomena that are microscopic or impossible to carry out in a school context due to their dangerousness. It is also possible to observe living systems and understand the activity of microscopical organisms [21]. Related to astronomy content, "AR can help students develop visuospatial skills", as pointed out by Ferrari et al. (2024) [22]. Dirgantara Deha et al. (2023) [23], referring that "technology itself also evokes practicality and creates a sense of illusion that makes students feel in out-of-reach locations while enabling visualizations and pragmatic experiences that cannot normally be observed or demonstrated through the classroom". In our review, some studies used AR to teach NS and Biology knowledge associated with experimental methodology, but without specifying the pedagogical strategies adopted in each of the groups. Part of these studies limited themselves to mentioning that a certain content was taught using AR in the experimental group and without using AR in the control group [24]. This does not mean that they did not use certain teaching strategies, but these were not sufficiently described. It is known that digital technologies and their various tools are more efficient when they are associated with certain pedagogical strategies, such as those proposed by the cognitive theory of multimedia learning [25-27] and the theory of cognitive load [28, 29] or by certain instructive models, such as 4C/ID [30-32]. In other words, technology *per se* does not seem to produce visible results in student learning [33–35].

The essential factor in improving or optimizing performance is to associate a certain technology, such as AR, with a specific teaching strategy or instructional model. In the review conducted on the present study, only the results of studies regarding the teaching of NS and Biology in non-higher education were included. It was our option to exclude from this analysis the context of Sciences *lato sensu*, as this term usually covers subjects aggregating several teaching areas like biology, mathematics, chemistry, and physics, or STEM, also a large cover of subjects, even if teaching strategies adopted were described. Evoking the previous argument, the absence of specific analysis regarding NS and Biology as teaching subjects and the existence of numerous apps available and accessible via smartphone and their ease integration into school learning to teach NS or Biology, we chose to carry out a Systematic Literature Review (SLR) and Meta-Analysis, as it is the most appropriate methodology to understand the effect size found in the studies under analysis and which allows conclusions to be generalized, overcoming possible distortions in individual studies [36]. We find our work relevant due to the absence of publications where SLR and meta-analysis are focused only on teaching and learning NS and Biology at the educational levels considered. Ferrari et al. (2024) [22] mention that "To maximize the effectiveness of AR, it's crucial to understand that its benefits differ in various learning environments". To support this observation, we start by analysing twelve literature reviews collected from 2014 to 2024 concerning AR in education, detailing them under the similar studies subsection. Subsequently, we present a brief reference of AR evolution and the most recent theoretical framework. Section 2 refers to the method, where PRISMA methodology was followed, considering publications after 2010, with data allowing a meta-analysis performance, i.e., number of participants per group, averages, and standard deviation. Section 3 presents results with a brief analysis, which are detailed under section 4 Discussion, to end on section 5 with a conclusion. We guided the present Systematic Literature Review by the following research questions:

*Q1.* In which NS and Biology teaching contexts, in non-higher education, has the application of AR been integrated?

*Q2.* What is the effect size on student learning outcomes when using AR in teaching of NS and Biology?

*Q3.* What is the effect size on student motivation when using AR in teaching of NS and Biology?

*Q4.* What are the advantages and the disadvantages of integrating AR into NS and Biology teaching on other dependent variables or outcomes?

*Q5.* Which learning strategies associated with AR have proven to be most efficient?

### *1-1- Similar Studies Concerning AR Uses on Education*

Our analysis of the existing literature review concerning the uses of AR on education emphasizes the presence of favourable aspects of AR in a learning context but also points out some constraints. The meta-review and cross-data analysis developed by Radu (2014) [37] considers 26 publications (all before 2012), and pointed out the effectiveness of AR on several topics compared to other media (books, videos, or computers) highlighting more efficient retention in long-term memory, improvement in performance, better physical machinery operating, and higher satisfaction. It also improved group collaboration, allowed to experience on phenomena impossible to operate in class and visualization of complex 3D content. It also reduced cognitive load and encouraged students' exploration and creativity. The least achieved aspects analysed by the author suggest the higher attentional demand from students (as they may tend to ignore important context or not be able to complete the task), may centre the class on the teacher, high-achieve students may not equally benefit from AR use, and low-ability readers may experience textual difficulties if large content is present.

In the systematic review presented by Akçayır & Akçayır (2017) [17], the hybrid immersive environment that is created in the combination of digital and real is highlighted, promoting critical thinking, problem-solving, communication and collaboration and also explain the positive aspects of learning results. The authors examined 68 research papers (from 2007 to 2015), and registered good results in students learning achievement, motivation, and attitude. They also consider relevant the guidance and immediate information presented by AR systems. These authors mentioned the cognitive load reduction on the student's working memory, and the possibility to visualize abstract concepts or unobservable phenomena. AR systems allow teachers to improve students' responsibility for making their own decisions since a major focus on the topic is achieved. These authors draw attention to certain less positive aspects related to usability (due to extensive interaction), possible cognitive overload (due to the number of materials or complexity of the task), errors concerning GPS (Global Positioning System) perceiving location or direction, and lack of class time to implement the activity.

Chen et al. (2017) [38] conducted a literature review analysing 55 papers from 2011 to 2016, highlighting the use of AR in various fields such as science lab experiments, mathematics, geometry, geography, ecology, and scientific issues, as well as in language learning and visual art. AR has been successfully integrated into academic fields like Engineering and Health, with a major advantage being the ability to visualize the unseen without specialized devices and to grasp abstract or complex concepts more easily. The review also points to the promotion of student-centred learning scenarios, improved learning performance, increased motivation, positive attitudes toward AR, and enhanced enjoyment. Additionally, better learning outcomes are linked to authentic graphical content and interactive experiences. While no negative aspects are mentioned, the need for further studies involving students of different ages and various learning scenarios is emphasised.

Garzón et al. (2019) [39] presented a systematic review and meta-analysis of 61 studies published between 2012 and 2018, highlighting gains in student learning and motivation, with a medium effect size on effective learning ($d = 0.64$). The study acknowledges that AR in education, as well as in fields like medicine, entertainment, and tourism, is still evolving. The medium effect size underscores the importance of continuing to develop strategies to increase the accessibility and effectiveness of AR in educational environments. An important point raised is the analysis of a study involving students with special needs, emphasizing the significance of engaging stakeholders in this area. On the downside, challenges such as the complexity of AR technology, the multitasking required to manage attention to various elements simultaneously, and resistance from teachers who may feel a loss of control over the content are noted.

The systematic review by Alzahrani (2020) [40], based on 28 studies published between 2009 and 2019, analysed publications focused exclusively on experimental research. AR in e-learning contexts is highlighted for its benefits to collaboration and interaction, mirroring face-to-face engagement. Student-centred kinaesthetic learning is noted for enhancing understanding and memory through 3D visualization, enabling faster and more effective learning of complex situations in e-learning systems. Additional improvements include enhanced focus, attention, concentration, amplified interest, and increased interaction with learning materials. Key challenges identified include information and cognitive overload, which may reduce learning effectiveness, and the complexity of the technology, which could lead to resistance from teachers. Other concerns include the cost of acquiring and maintaining the technology, as well as connectivity and technical issues.

Pedaste et al. (2020) [18] conducted a systematic review of 15 studies from 2015 to 2020, focusing on the integration of AR in inquiry-based learning (IBL). None of the articles reviewed integrated AR across all phases of IBL, with most studies applying AR only in one or occasionally two of the five inquiry phases. AR usage was predominantly reported in the conceptualization or investigation phases. The review explains the potential for integrating AR in each phase of IBL and reflects on the implementation across all phases. Overall, beneficial effects were observed on cognitive, metacognitive, motivational, emotional, and collaborative aspects. The lack of studies exploring AR incorporation in all IBL phases is noted as a limitation. Avila-Garzon et al. (2021) [41] conducted a bibliometric analysis covering twenty-five years of research, from 1995 to 2020, comprising a total of 3,475 documents. The analysis highlights that AR promotes new forms of interaction with topics, enhances visualization, and reduces cognitive load. The potential for teachers to create or modify content for AR learning scenarios is also emphasized. However, access to technology is identified as a limitation, as disparities in access could exacerbate educational inequalities.

Law & Heintz (2021) [42] conducted a systematic review of 49 papers from 2000 to 2020, primarily focusing on the usability and user experience of AR educational applications. Mobile devices were noted for having low GPS accuracy during outdoor learning experiences, and visibility issues caused by sunlight were also highlighted. Despite being considered a positive aspect in several systematic literature reviews, the small screens of mobile devices may pose usability problems, while larger screens, like tablets, may cause fatigue due to their weight. Marker-based interactions were identified as needing improvement, particularly due to detection faults. The review also stressed the importance of considering students' age when integrating AR, especially for younger children who may become frustrated if their motor or spatial cognition skills are underdeveloped. A lack of usability analysis in most studies was observed, as the primary focus tended to be on educational impacts. De Lima et al. (2022) [43] provided a critical literature analysis based on 169 studies published between 2008 and 2020, emphasizing that AR educational technologies enhance learning outcomes and promote motivation. The importance of involving teachers in the process of implementing student-centred AR learning scenarios was also emphasized.

Zhang et al. (2022) [44] conducted a systematic review and meta-analysis evaluating 129 studies from 2000 to 2020, highlighting the increase in AR-supported instruction, particularly in elementary schools, and the widespread use of mobile devices for AR due to their portability, standalone capabilities, and interactivity. Tablets were also noted for their large screens and better performance. A large effect size on learning outcomes ($g = 0.919$) was identified, with discipline, scaffolding, and rounds of practice as significant moderators. The ideal AR app for K-12 is described as being portable, flexible, highly interactive, reliable, and sustainable, with low cost and accessibility. Chang et al. (2022) [45] conducted a meta-analysis based on 134 experimental or quasi-experimental studies from 2012 to 2021, focusing on AR in education. A nearly large effect size ($g = 0.74$) on students' performance was reported, with a medium effect size on knowledge and skill ($g = 0.65$), though significant variances among studies were noted. Meta-regression results suggest that 3D visualizations in AR have a smaller effect size compared to studies using 2D visualizations or images alone. An analysis across educational levels indicated an equally positive effect at various levels. Usability issues, technical problems, and technology acceptance were also identified as important considerations when using AR.

Cao & Yu (2023) [36] conducted a meta-analysis based on 28 publications, from 2016 to 2023. They found that AR-assisted education has a positive impact on learners, leading to higher learning achievements and increased motivation levels. The authors emphasized that AR enhances the learning process, stimulates student engagement, and improves academic performance. However, they also noted several challenges, including technical issues, cost, connectivity problems, and privacy concerns. Koumpouros (2024) [46] conducted a Systematic Bibliographic Review based on 73 studies, from 2016 to 2020. The author highlighted the innovative aspects of AR in learning, such as providing 3D visualization of objects, supporting in-depth understanding, and improving knowledge retention. Koumpouros et al. [46] also recommended the need for more studies to explore different methodologies and study designs in AR education, as well as the long-term effects of AR on learning outcomes. Limitations of AR usage identified by the author included technical issues, compatibility problems, and the need for significant equipment resources.

The systematic reviews of the literature analysed highlight that in the majority of studies that used AR in teaching and learning processes, the results are positive in terms of student learning and motivation, as well as in other variables, where visualization stands out of phenomena not visible by observation with the naked eye, greater interaction with learning tasks, and increased collaboration between students. The studies analysed also point out some difficulties where technical problems stand out, such as the small size of cell phone screens to observe certain phenomena, the lack of technical preparation of some teachers in the use of AR, and difficulties associated with accessibility. There were also contradictory results. Among these are studies that consider that the use of AR made it possible to reduce cognitive and informational load and others that report the opposite. All the authors of the studies analysed say that it is necessary to continue developing research using AR in different learning contexts and with students of different ages, developing primary studies and meta-studies. It is in this last axis that our study is inserted in two areas little explored in literature above all among students aged 5 to 18.

### *1-2- Augmented Reality*

The term augmented reality is attributed to Tom Caudell, a researcher at Boeing, and was coined in the mid-1990s [39, 42, 47-50]. It is accepted that this concept emerged in the 1960s, through the work of Sutherland [51, 52]. AR is seen as a three-dimensional simulation environment created using software and hardware to provide the user with a realistic interaction experience [16]. This concept is also understood as corresponding to all situations where the real world is augmented by the presentation of a virtual object (originated by computer graphics), making it possible to define the concept of the virtuality continuum [53]. AR is a system that associates: (i) the combination of real and virtual objects, (ii) the interaction with these objects in real-time, and (iii) a combination of the real and the virtual in a three-dimensional way [54]. Four levels can be defined for AR: level 0, use of QR codes (quick read) to activate a hyperlink; level 1, use of markers that convert elements into activators of 3D images superimposed on the real world; level 2, use of images or real objects as activators; level 3, use of specific glasses to integrate AR into the real world [55]. AR continues to be a widely evolving field in various areas such as healthcare, retail, digital commerce, tourism, manufacturing, and maintenance [56].

The evolution of the theoretical framework in which AR is integrated has been updated to include a mixed reality that is expressed through the virtuality continuum proposed by Milgram and Kishino (1994) [53]. This virtuality continuum oscillates between environmental reality (real world), through augmented reality (not very immersive), to the virtual environment (fully immersive). Mann et al. [57, 58] expand this axis by increasing the “realities” that can be included, such as virtual, augmented, mixed, or mediated. These authors propose the expression “multimediated reality” or “all realities” (“All reality” or “All R”), as they understand it to be multidimensional, multimodal, multisensory, multiscale, multidisciplinary, and multivigilant. Regarding AR, these authors highlight the superimposition of the real world without altering it, but this slight immersion is altered when viewing a video through a system of glasses, an aspect that superimposes the virtual in the real world, although not in an intentional way. They think they are facing a mediated reality. Bekele & Champion (2019) [59] present a redefinition of mixed reality proposed by Milgram & Kishino (1994) [53], integrating the perspective of user experience and valuing the user-virtual reality interaction. These authors think that AR promotes an improvement in the visualization of the real world by integrating virtual elements, even if virtual elements are completely superimposed on the surrounding physical world, as the relationship is always established between the user and the virtual elements. They emphasize that the real world is always present and is dominant in this relationship, with virtual elements being an added value for the perception of the real world.

Skarabez et al. (2021) [54] reiterate in the proposed review the importance of the user's role. They understand that there is no true continuum as expressed by Milgram & Kishino (1994) [53], as full virtual reality cannot be achieved as it occurs in a real world. They express the importance of the term mixed reality, but from a broader perspective. These authors warn about the need to clarify AR as distinct from the augmented virtual due to the great overlap of the virtual in the real world. Thus, they seek to create a three-dimensional taxonomy, relating the axes of extension of worldly knowledge—seeking to describe the modelling of the real world (extent of world knowledge continuum), reproduction fidelity—technology's ability to reliably reproduce the real world (reproduction fidelity), and extension of the presence metaphor—level of graphic conformation of the world and interpretation of the user experiencing the mixed reality environment (extent of presence metaphor). Mann et al. (2023) [60], seeking to clarify possible confusion and even overlapping definitions, present different realities: virtual, augmented, (deliberately) diminished, mixed, mediated, multi-mediated, and phenomenological. These authors clarify that, despite some similarities between AR and virtual reality, there is no complete blocking of reality, given that the virtual aspects are embedded in the experience that occurs in the real world, with both being observed simultaneously. They also present a vision of AR as phenomenological, as it results from the interaction between the user, AR, and the phenomena of the surrounding environment. Visually they organize a Venn diagram, placing virtual reality as a subset of AR and AR as a subset of mixed reality.

## 2- Method

### *2-1- Data Collection*

In the present study, the PRISMA methodology—Preferred Reporting Items for Systematic Reviews [61]—was used, and research was carried out through the databases EBSCO, ScienceDirect, Scopus, Springer Link, Taylor & Francis, and Web of Science, looking for publications after 2010. The terms augmented reality (augmented reality / realidad aumentada / réalité augmentée), science teaching (science teaching / enseñanza de las ciencias / enseignement des sciences) were integrated, and, whenever the operators allowed it, the terms virtual reality (virtual reality / realidad virtual / réalité virtuelle) and university (university / Universidad / université) were excluded, with searches in English, French, and Spanish, as shown in Table 1.

**Table 1. Databases, search terms and records of the systematic literature review process**

| Databases | Search Terms | Records |
|---|---|---|
| EBSCO | "augmented reality" AND "science teaching" NOT "virtual reality" NOT "university" | 38 |
| | "realidad aumentada" AND "enseñanza de las ciencias" NOT "realidad virtual" NOT "universidad" | 16 |
| | "réalité augmentée" AND "enseignement des sciences" NOT "réalité virtuelle" NOT "université" | 2 |
| ScienceDirect | 'augmented reality' AND 'science%teaching' NOT 'virtual reality' NOT 'university' | 286 |
| | 'realidad aumentada' + 'enseñanza%ciencias' - 'realidad virtual' - 'universidad' | 15 |
| | 'réalité augmentée' + 'enseignement%sciences' - 'réalité virtuelle' - 'université' | 11 |
| Scopus | ALL (("augmented reality" AND "science teaching") AND NOT ("virtual reality") AND NOT ("university")) AND PUBYEAR > 2010 | 95 |
| | ALL (("realidad aumentada" AND "enseñanza de las ciencias") AND NOT ("realidad virtual") AND NOT ("universidad")) AND PUBYEAR > 2010 | 19 |
| | ALL (("réalité augmentée" AND "enseignement des sciences") AND NOT ("réalité virtuelle") AND NOT ("université")) AND PUBYEAR > 2010 | 0 |
| Springer Link | ('augmented reality' AND 'science teaching') AND NOT ('virtual reality' OR 'university') | 176 |
| | ('realidad aumentada' AND 'enseñanza de las ciencias') AND NOT ('realidad virtual' OR 'universidad') | 0 |
| | ('réalité augmentée' AND 'enseignement des sciences') AND NOT ('réalité virtuelle' OR 'université') | 6 |
| Taylor & Francis | “augmented reality” AND “science teaching” | 38 |
| | “realidade aumentada” AND “enseñanza de las ciencias” | 1 |
| | “réalité augmentee” AND “enseignement des sciences” | 0 |
| Web of Science | ((((ALL=("Augmented reality")) AND ALL=("Science teaching")) NOT ALL=("Virtual reality")) NOT ALL=("university")) AND PY=(2010-2022) | 13 |
| | ((((ALL=("realidad aumentada")) AND ALL=("enseñanza de las ciencias")) NOT ALL=("realidad virtual")) NOT ALL=("universidad")) AND PY=(2010-2022) | 0 |
| | ((((ALL=("réalité augmentée")) AND ALL=("enseignement des sciences")) NOT ALL=("réalité virtuelle")) NOT ALL=("université")) AND PY=(2010-2022) | 0 |

## *2-2- Search Results*

A total of 716 articles were obtained from the six databases consulted, with three studies obtained through Google Scholar and two studies from Wiley Online Library being added, which were considered equally relevant to this work, as shown in Figure 1.

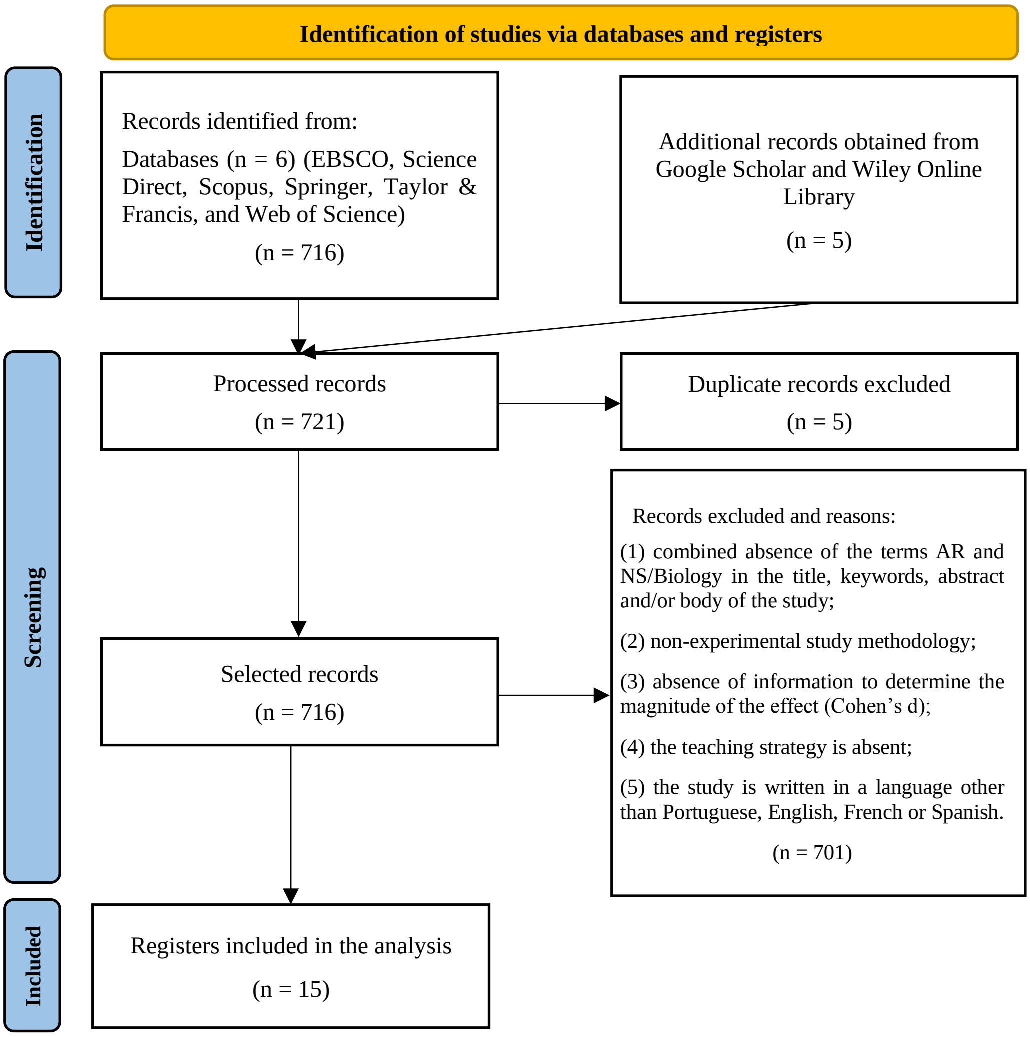


**Figure 1. Flowchart of the PRISMA methodology for the systematic review**

### *2-3- Inclusion and Exclusion Criteria*

In the selection process, 721 articles were obtained, five were excluded because they were repeated and the exclusion criteria were applied to the remaining 716: (1) combined absence of the terms AR and NS or Biology in the title, keywords, abstract and/or body of the article, having read it whenever necessary; (2) non-experimental study methodology, including only quasi-experimental studies, as they took place in a school context [62, 63]; (3) lack of information that prevented determining the effect size (Cohen's *d*), as one of the objectives of the analysis is to determine the effect size; (4) absence of a description of the teaching strategy, which would allow us to evaluate which are the most appropriate, as this is also one of the objectives of this work; (5) be in a language other than Portuguese, English, French or Spanish, as these are accessible to the authors of this work. From this application, 706 studies were excluded and 15 were preserved, distributed across seven databases as illustrated in Table 2 and summarized in Figure 2 and by study country in Figure 3.

**Table 2. Identification of the 15 studies for the database, country, and study methodology**

| Authors (date) | Database | Country | Study methodology |
|---|---|---|---|
| Chen et al. (2019) [2] | Springer | Taiwan | Quasi-experimental |
| Chien et al. (2019) [14] | Springer | Taiwan | Quasi-experimental |
| Chen (2020) [64] | Spinger | Taiwan | Quasi-experimental |
| Wen et al. (2023) [65] | Spinger | Singapore | Quasi-experimental |
| Weng et al. (2020) [7] | Scopus | Indonesia | Quasi-experimental |
| Huang et al. (2022) [3] | Scopus | Taiwan | Quasi-experimental |
| Chang et al. (2016) [13] | Taylor & Francis | Taiwan | Quasi-experimental |
| Wang et al. (2022) [15] | Taylor & Francis | China | Quasi-experimental |
| Erbas et al. (2019) [66] | Wiley | Turkey | Quasi-experimental |
| Arici et al. (2022) [4] | Wiley | Turkey | Quasi-experimental |
| Karagozlu (2018) [67] | Web of Science | n.d. | Quasi-experimental |
| Keçeci et al. (2021) [9] | EBSCO | Turkey | Quasi-experimental |
| Fokides et al. (2018) [1] | Google Scholar | Greece | Quasi-experimental |
| Omurtak et al. (2022) [8] | Google Scholar | Turkey | Systematic mixed-method, quasi-experimental design |
| Özeren et al. (2023) [6] | Google Scholar | Turkey | Quasi-experimental |

Note. n.d.: not defined.

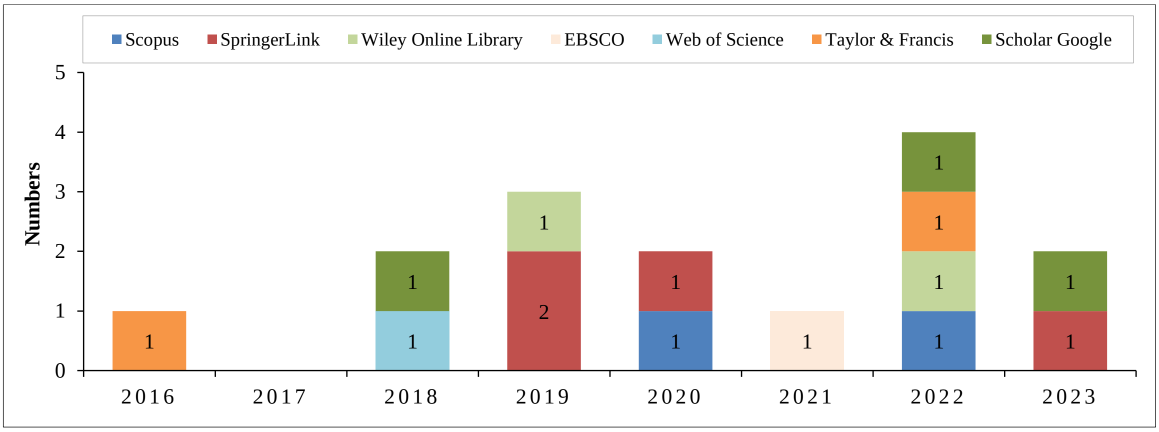


**Figure 2. Studies obtained, analysed by database and year of publication**

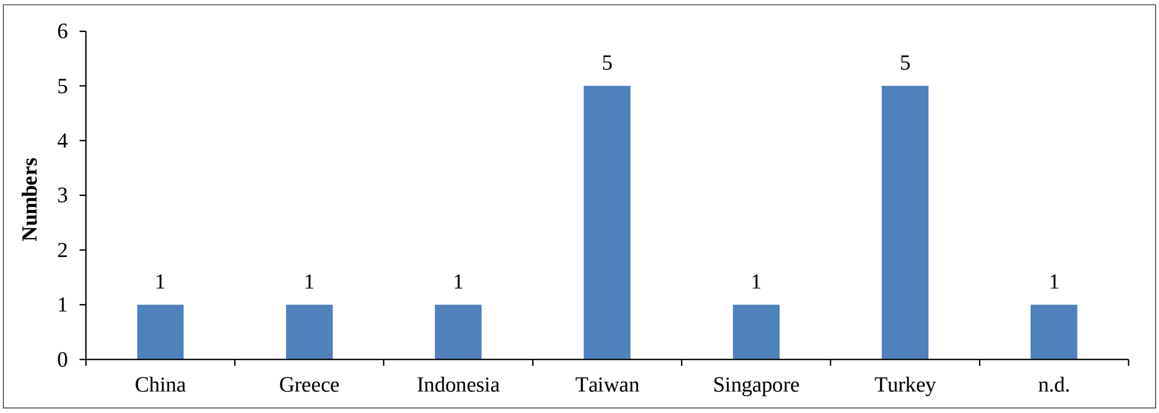


**Figure 3. Analysed studies by country**

## 3- Results

The results are presented following the research questions previously posed: first, the contexts of application of AR; second, calculations of the effect size on the learning results of students who used AR when compared to those who did not use it; third, from the selected studies, the advantages of integrating AR in student motivation and other variables analysed in the studies are indicated; and fourth and lastly, we summarize the teaching strategies that proved to be most efficient in improving student performance.

### 3-1- Augment Reality Application Contexts

In the analysis conducted, there was a heterogeneity in the topics studied and in the duration of the interventions. Regarding the topics covered, 26.67% ($n$ = 4) of studies on plants or related to them were recorded; 20.00% ($n$ = 3) on human systems; 13.33% ($n$ = 2) on the cell; 6.67% ($n$ = 1) on insects, ecosystems, and food; 13.33% ($n$ = 2) of the studies do not mention the topic covered. The duration of the investigations presented in the studies were grouped into two sets: interventions of up to 180 minutes, corresponding to 26.67% ($n$ = 4) and of more than three weeks corresponding to 60.00% ($n$ = 9), and the remaining 13.33% ($n$ = 2) the information was missing in the studies analysed. These data are organized in Table 3. Another interesting aspect related to the apps used was observed: in 46.67% ($n$ = 7) of the studies the app was created specifically for the intervention; in 20.00% ($n$ = 3) an app that is still available on the market was used; in 6.67% ($n$ = 1) an app already discontinued; and in 26.67% ($n$ = 4) it does not refer to the app used in the intervention.

**Table 3. Identification of the fifteen studies for subject, theme, school year, age, and duration**

| Authors (date) | School subject/ Course | Learning topic | Grade | ISCED | Age in years | Duration |
|---|---|---|---|---|---|---|
| Chen et al. (2019) [2] | Natural Sciences | Ecosystems | 5th | 1 | 11 | n.d. |
| Chien et al. (2019) [14] | Natural Sciences | Plants | 3rd | 1 | n.d. | 110 min (15+40+40+15) |
| Chen (2020) [64] | Natural Sciences | Insects | 4th | 1 | 9.5 (average) | 2 weeks + 40 min + 1 week (field trip to learning park) + 40 min |
| Wen et al. (2023) [65] | Natural Sciences | Plants | 5th | 1 | 11 to 12 | 3 weeks |
| Weng et al. (2020) [7] | Biology | Food biotechnology | 9th | 2 | n.d. | 90 min (20+5+45+20) |
| Huang et al. (2022) [3] | Natural Sciences | Plant and leaf arrangements | 3rd | 1 | n.d. | n.d. |
| Chang et al. (2016) [13] | Natural Sciences | Flora | 4th | 1 | n.d. | 180 min (120 learning fundamental + 60 strengthening) |
| Wang et al. (2022) [15] | Biology | Respiratory system | 3rd | 1 | n.d. | 180 min (3 × 60 min) |
| Erbas et al. (2019) [66] | Natural Sciences | Cell and Cell division | 9th | 2 | n.d. | 7 weeks |
| Arici et al. (2022) [4] | Biology course | n.d. | 7th | 2 | 11 | 8 weeks |
| Karagozlu (2018) [67] | Science class | n.d. | 7th | 2 | 12 | 14 weeks |
| Keçeci et al. (2021) [9] | Science course | Support and movement, respiratory, and circulatory systems. | 6th | 2 | n.d. | 8 weeks |
| Fokides et al. (2018) [1] | Science | Respiratory and circulatory systems | 6th | 1 | 11 to 12 | 1 month (4 × 2h sessions) |
| Omurtak et al. (2022) [8] | Biology | Unit: cell; Subject: cellular structures and their functions | 9th | 2 | 15 | 6 weeks |
| Özeren et al. (2023) [6] | Science course | Cell and Cell division unit | 7th | 2 | n.d. | 4 weeks |

Note. n.d.: not defined.

### 3-2- Determination of Effect Size

#### 3-2-1- Effect Size of Using AR in Student Learning

The option to determine the effect size using Cohen's $d$ was made because it is a widely used test [63, 68], particularly in meta-analyses, and its determination is not "affected by the size of the sample(s)" [69]. These authors indicate: 0 to 0.20 - small effect; 0.21 to 0.50 - modest effect; 0.51 to 1.00 - moderate effect; > 1.00 - strong effect. Cohen (1988) [70] defines its determination using the formula:

$$d = \frac{m_A - m_B}{\sigma} \quad (1)$$

where $m_A$ e $m_B$ are the means of the populations in the original units and $\sigma$ is the standard deviation of the two populations. The effect size was determined in this meta-analysis using SPSS v.29 software. In the studies analysed, there was a control group where a certain learning strategy was used without the use of AR and the experimental group with the application of the same learning strategy and use of AR. Information was collected from each study on the number of students for each group (control and experimental), the respective post-test means and standard deviations, data that are organized in Table 4.

**Table 4. Number of students, post-test results and standard deviations comparing the control (without AR) and experimental (with AR) groups in the 15 studies**

| Authors (date) | Nt | Ne | Nc | Pos_Me | Pos_SDe | Pos_Mc | Pos_SDc |
|---|---|---|---|---|---|---|---|
| Chen et al. (2019) [2] | 65 | 31 | 34 | 81.87 | 10.31 | 72.12 | 16.20 |
| Chien et al. (2019) [14] | 45 | 23 | 22 | 82.87 | 10.55 | 84.55 | 13.56 |
| Chen (2020) [64] | 49 | 24 | 25 | 81.19 | 13.80 | 78.28 | 20.45 |
| Wen et al. (2023) [65] | 73 | 36 | 37 | 16.27 | 2.05 | 15.97 | 2.61 |
| Weng et al. (2020) [7] | 68 | 34 | 34 | 83.43 | 11.50 | 81.34 | 11.07 |
| Huang et al. (2022) [3] | 109 | 57 | 52 | 90.09 | 7.08 | 81.08 | 12.30 |
| Chang et al. (2016) [13] | 55 | 28 | 27 | 3.96 | 0.79 | 3.62 | 0.92 |
| Wang et al. (2022) [15] | 74 | 38 | 36 | 58.47 | 23.55 | 58.85 | 26.78 |
| Erbas et al. (2019) [66] | 40 | 20 | 20 | 5.05 | 1.67 | 5.25 | 1.37 |
| Arici et al. (2022) [4] | 61 | 30 | 31 | 70.80 | 10.82 | 57.03 | 13.86 |
| Karagozlu (2018) [67] | 147 | 77 | 70 | 79.11 | 11.72 | 53.99 | 16.58 |
| Keçeci et al. (2021) sc1 [9] | 46 | 23 | 23 | 16.26 | 3.50 | 10.95 | 4.58 |
| Keçeci et al. (2021) sc2 [9] | 97 | 48 | 49 | 20.12 | 1.63 | 18.18 | 2.32 |
| Fokides et al. (2018) [1] | 50 | 25 | 25 | 30.68 | 3.61 | 21.40 | 7.90 |
| Omurtak et al. (2022) [8] | 38 | 17 | 21 | 28.06 | 2.11 | 14.86 | 2.37 |
| Özeren et al. (2023) [6] | 54 | 27 | 27 | 88.89 | 2.95 | 65.93 | 6.78 |

Note. Nt: total number of students; Ne: number of students in the experimental group; Nc: number of students in the control group; Pos_Me: post-test average in the experimental group; Pos_SDe: standard deviation of the post-test in the experimental group; Pos_Mc: post-test average in the control group; Pos_SDe: standard deviation of the post-test in the experimental group; Pos_Mc: mean of the post-test in the control group; Pos_SDc: standard deviation of the post-test in the control group; sc1: school 1; sc2: school 2 (since schools 1 and 2 differ in socio-economic background).

Table 5 presents the results of effect size on student learning resulting from the use of AR in each of the 15 studies analysed and in Table 6 the result for the set of 15 studies, followed, in Figure 4, by the graph of forest plot that allows to better visualize these results.

**Table 5. Effect size for each study regarding the learning effects for using AR in the 15 analysed studies**

| Authors (date) | Cohens' *d* | Std. Error | Z | Sig. (2-tailed) | 95% Confidence Interval | | *p* value | Weight | Weight (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Lower | Upper | | | |
| Chen et al. (2019) [2] | 0.711 | 0.256 | 2.777 | 0.005 | 0.209 | 1.213 | 0.005 | 0.452 | 6.37 |
| Chien et al. (2019) [14] | -0.139 | 0.299 | -0.464 | 0.642 | -0.724 | 0.447 | 0.642 | 0.447 | 6.30 |
| Chen (2020) [64] | 0.166 | 0.286 | 0.580 | 0.562 | -0.395 | 0.727 | 0.562 | 0.449 | 6.32 |
| Wen et al. (2023) [65] | 0.128 | 0.234 | 0.546 | 0.585 | -0.331 | 0.587 | 0.585 | 0.454 | 6.40 |
| Weng et al. (2020) [7] | 0.185 | 0.243 | 0.762 | 0.446 | -0.291 | 0.662 | 0.446 | 0.454 | 6.38 |
| Huang et al. (2022) [3] | 0.909 | 0.201 | 4.511 | <0.001 | 0.514 | 1.303 | 0.000 | 0.457 | 6.44 |
| Chang et al. (2016) [13] | 0.397 | 0.272 | 1.458 | 0.145 | -0.137 | 0.931 | 0.145 | 0.450 | 6.34 |
| Wang et al. (2022) [15] | -0.015 | 0.233 | -0.065 | 0.948 | -0.471 | 0.441 | 0.948 | 0.455 | 6.40 |
| Erbas et al. (2019) [66] | -0.131 | 0.317 | -0.414 | 0.679 | -0.751 | 0.490 | 0.679 | 0.445 | 6.27 |
| Arici et al. (2022) [4] | 1.105 | 0.275 | 4.020 | <0.001 | 0.566 | 1.644 | 0.000 | 0.450 | 6.34 |
| Karagozlu (2018) [67] | 1.764 | 0.195 | 9.066 | <0.001 | 1.383 | 2.145 | 0.000 | 0.458 | 6.45 |
| Keçeci et al. (2021) sc1 [9] | 1.303 | 0.325 | 4.013 | <0.001 | 0.666 | 1.939 | 0.000 | 0.444 | 6.25 |
| Keçeci et al. (2021) sc2 [9] | 0.966 | 0.215 | 4.501 | <0.001 | 0.545 | 1.387 | 0.000 | 0.456 | 6.42 |
| Fokides et al. (2018) [1] | 1.511 | 0.321 | 4.712 | <0.001 | 0.882 | 2.139 | 0.000 | 0.445 | 6.26 |
| Omurtak et al. (2022) [8] | 5.846 | 0.746 | 7.839 | <0.001 | 4.384 | 7.307 | 0.000 | 0.370 | 5.21 |
| Özeren et al. (2023) [6] | 4.391 | 0.503 | 8.737 | <0.001 | 3.406 | 5.377 | 0.000 | 0.417 | 5.87 |

Note. sc1: school 1; sc2: school 2 (since schools 1 and 2 differ in socio-economic background).

**Table 6. Effect size for the overall effect of the 15 studies analysed on the effect from using AR on learning**

| | Effect Size | Std. Error | Z | Sig. (2-tailed) | 95% Confidence Interval | | 95% Prediction Interval[a] | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Lower | Upper | Lower | Upper |
| **Overall** | 1.126 | 0.3752 | 3.000 | 0.003 | 0.390 | 1.861 | -2.118 | 4.369 |

Note. a: Based on t-distribution.

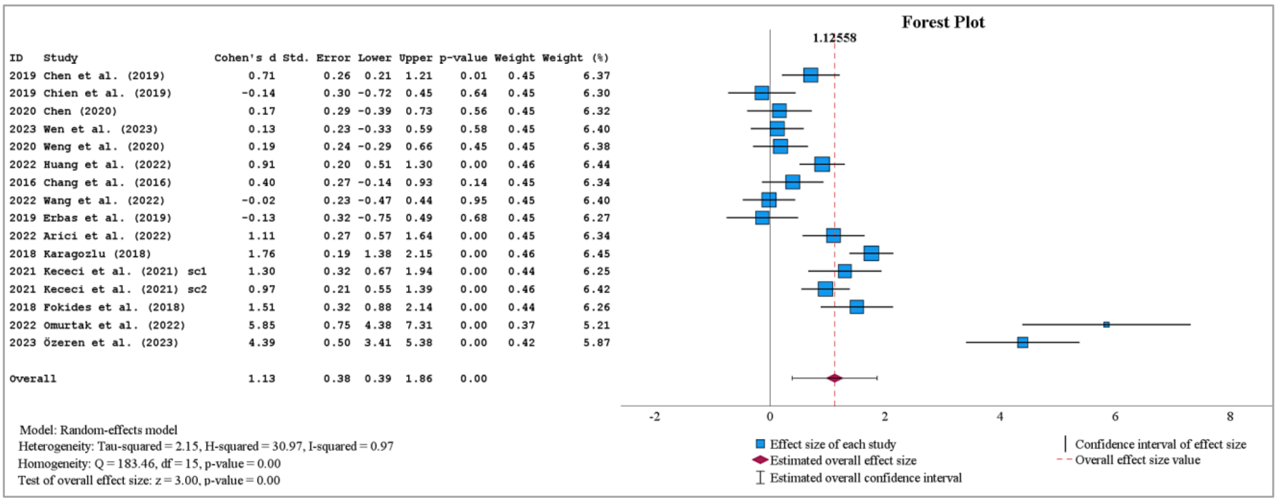


**Figure 4. Forest plot for the effect size on learning from AR use in the 15 selected studies**

The global analysis of the data allows us to observe a strong effect size (*d* = 1.13 [0.39; 1.86]) in students who used AR compared to those who did not use it. These results, according to Coe (2002) [71], allow us to expect that an average student in the experimental group would perform between 84% and 88% better than a student in the control group who were initially equivalent. The heterogeneity test shows a high heterogeneity value, with $I^2$ = 97%, value that does not depend on the number of studies included [72, 73]. In the homogeneity analysis, the value $Q$ = 183.46, $p < 0.001$ ($df$ = 15), suggests that the effect of integrating AR on learning is observed in the performance of students who used it. Thus, it was understood that in this meta-analysis a heterogeneous nature of the studies was present and that, therefore, it was justified to use the random effect model to determine the effect size [74, 75], an aspect that is based on the analysis of the very identical values obtained in the weight and percentage of the weight of the articles analysed (Table 5 and Figure 4). It is, however, important to assess the existence of bias between the effect size and the reliability (reciprocal value of variance), an aspect that can be determined using the Egger test. The analysis carried out allowed to obtain a coefficient of - 1.915 as the intercept value, with $p$ = 0.007. Therefore, this value seems to suggest a possible publication bias, but it may also be associated with small samples with great heterogeneity, as happens in the selected [36]. This aspect may be associated with the contexts of each country, the different levels of education, and the different themes [76]. This bias does not translate into a change in the effect size in favour of studies with a smaller number of students when comparing the values with those obtained in the fixed effect analysis. Any publication bias does not compromise the validity of the meta-analysis carried out, as the analysis of the funnel plot (Figure 5) shows.

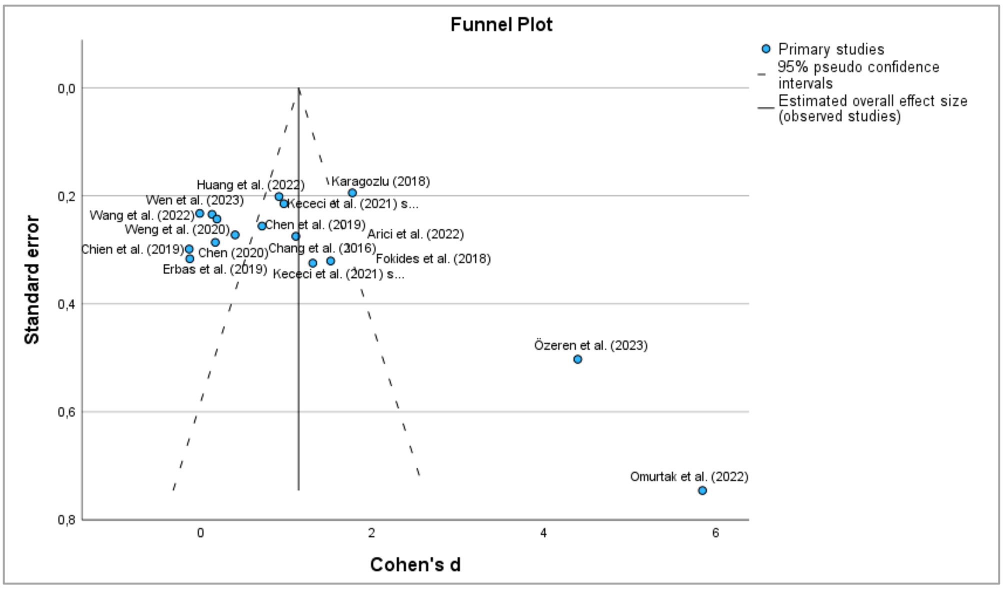


**Figure 5. Funnel plot for the meta-analysis of the effect size for AR use in the 15 selected**

It can be observed the standard error on the vertical axis and the effect size on the horizontal axis (Cohen's *d*) with a 95% confidence interval and a vertical marker indicating the global value of the amplitude of the effect in all the studies analysed. However, it was calculated, through the CMA software, the number of studies necessary for *p-value* > *α*, having obtained a value of 467 (Table 7).

**Table 7. Classical fail-safe N for metanalysis AR effect on students' achievement**

| Bias condition | |
|---|---|
| Z-value for observed studies | 11.10485 |
| P-value for observed studies | 0.000 |
| Alpha | 0.050 |
| Tails | 2 |
| Z for alpha | 1.960 |
| Number of observed studies | 15 |
| Number of missing studies that would bring p-value > alpha | 467 |

According to Wijaya et al. (2022) [77] Mullen's formula assumes that when:

$$\frac{N}{5K + 10} > 1 \quad (2)$$

it can be said that there is a low risk of publication bias. In this way, it was possible to determine a value:

$$\frac{467}{5*15 + 10} = 5.49 \quad (3)$$

which is greater than one, confirming the small publication bias in this meta-analysis. The list of studies shows that it is not possible to establish an obvious relationship between the country, the sample size, and the effect size, organizing, in Figure 6, an analysis of these data in alphabetical order of the country of origin and chronological order of the studies.

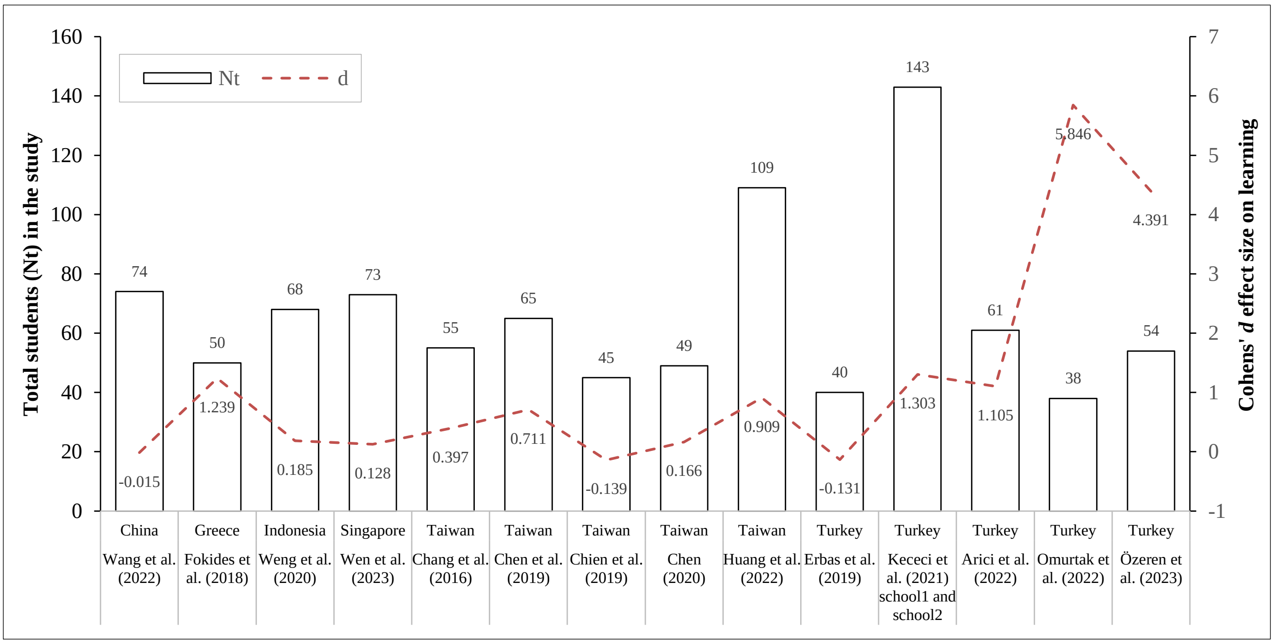


**Figure 6. Comparison between country, sample size and effect size in the 14 studies that allow for this comparison**

### *3-2-2- Effect Size of Using AR on Students' Motivation*

The same methodology previously presented was followed to determine the effect size on students' motivation to learn with and without the use of AR. However, not all the 15 studies analysed presented this dimension. Only in six was the study of motivation present as shown in Table 8.

**Table 8.** Effect size for each study regarding the effects on motivation for learning resulting from the use of AR

| Authors (date) | Effect Size | Std. Error | Z | Sig. (2-tailed) | 95% Confidence Interval | | Weight | Weight (%) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Lower | Upper | | |
| Chien et al. (2019) [14] | 0.548 | 0.2529 | 2.166 | 0.030 | 0.052 | 1.044 | 15.630 | 20.2 |
| Chen (2020) [64] | 0.375 | 0.2883 | 1.302 | 0.193 | -0.190 | 0.940 | 12.033 | 15.5 |
| Chang et al. (2016) [13] | 0.717 | 0.2783 | 2.576 | 0.010 | 0.172 | 1.262 | 12.916 | 16.7 |
| Wang et al. (2022) [15] | 0.460 | 0.2356 | 1.954 | 0.051 | -0.001 | 0.922 | 18.010 | 23.3 |
| Erbas et al. (2019) [66] | 0.460 | 0.3204 | 1.436 | 0.151 | -0.168 | 1.088 | 9.742 | 12.6 |
| Omurtak et al. (2022) [8] | 0.550 | 0.3323 | 1.656 | 0.098 | -0.101 | 1.202 | 9.056 | 11.7 |

In this table it can be seen the values for each of the six studies and in Table 9 for all, followed by the forest plot (Figure 7).

**Table 9.** Effect size for the overall effect of the six studies analysed on the effect from using AR on learning motivation

| | Effect Size | Std. Error | Z | Sig. (2-tailed) | 95% Confidence Interval | | 95% Prediction Interval[a] | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Lower | Upper | Lower | Upper |
| **Overall** | 0.518 | 0.1137 | 4.558 | <0.001 | 0.295 | 0.741 | 0.203 | 0.834 |

Note. a: Based on t-distribution.

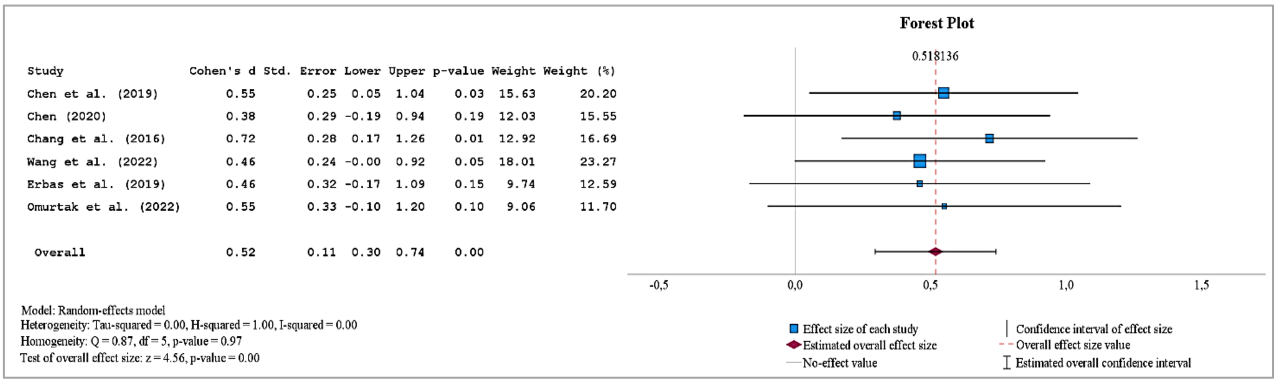


**Figure 7.** Forest plot for the effect size on learning motivation from AR use in six studies

### *3-2-3- Effect Size of AR Use on Other Dependent Variables or Outcomes*

The value of the effect size was also surveyed for other variables analysed in the various studies that are summarised in Table 10. In the studies analysed, the following statistically non-significant results of the integration of AR in learning were recorded: (i) Chien et al. (2019) [14] in evaluating the domains of understanding and memorization, from Bloom's taxonomy, where the authors indicate that the learning results after the activity developed with AR are not significantly ($p > 0.05$) different, when compared to the same strategy without AR; (ii) Chang et al. (2016) [13], in the follow-up evaluation they carried out of student learning, they obtained a small effect size ($d = 0.12$). In the remaining studies, moderate to strong effect size values were found [2, 14, 15], concerning the variables summarized in Table 10.

**Table 10.** Effect size for other variables in each study using AR

| Authors (date) | Variable | Nt | Ne | Nc | Me | SDe | Mc | SDc | *d* | *p-value* |
|---|---|---|---|---|---|---|---|---|---|---|
| Chen et al. (2019) [2] | ARMCM | 65 | 31 | 34 | 4.467 | 0.396 | 4.084 | 0.542 | 0.80 | <0.01 |
| Chien et al. (2019) [14] | Blooms' analysis | 45 | 23 | 22 | 38.430 | 6.200 | 33.860 | 8.180 | 0.63 | <0.05 |
| | Comprehension | | | | *23.650* | *5.900* | *22.670* | *4.600* | *0.58* | *>0.05* |
| | Remember | | | | *20.780* | *6.730* | *23.910* | *3.650* | *0.57* | *>0.05* |
| | Observation-based | | | | 2.650 | 0.770 | 2.140 | 0.820 | 0.64 | <0.05 |
| Chang et al. (2016) [13] | Delayed test | 55 | 28 | 27 | *7.530* | *1.310* | *6.070* | *1.290* | *0.12* | *0.00* |
| Wang et al. (2022) [15] | Flow experience | 74 | 38 | 36 | 4.589 | 0.484 | 4.006 | 0.645 | 1.02 | <0.001 |
| | Cognitive load | | | | 1.934 | 0.961 | 2.437 | 0.692 | 0.73 | <0.01 |

Note. ARMCM: Augmented reality multidimensional concept map; italic data refers to data not favourable to achievements on learning with AR use.

### *3-3- Advantages and Disadvantages of Integrating AR into the Teaching of Biology and NS*

#### *3-3-1- Advantages*

The advantages described by the authors of the 15 studies analysed, using the same terms they mentioned, were grouped into two categories: cognitive and academic advantages and affective and personal advantages. The first category included the following terms: learning, understanding, performance, construction of learning, critical thinking, problem-solving, cognitive load, analysis, and higher-level performance (these two integrated into Bloom's taxonomy). The following terms were included in the second category: motivation, interest, satisfaction, focus, collaboration, self-control, positive attitude, and interaction with the environment. Thus, we can mention that in the first category we found 33.33% of studies ($n$ = 5) [1-3, 8, 64] who report advantages of using AR in learning, associated with learning strategies and, with identical representation, 33.33% ($n$ = 5), better academic performance [2, 4, 9, 67]. In the second category, we highlight 26.67% of studies ($n$ = 4) that indicate students' motivation is favoured [6, 13, 15, 66]. We organise this survey in Table 11 and illustrate it in Figure 8.

**Table 11. Organization of the advantages, app and disadvantages of AR integration**

| Authors (date) | Academic | | | | | | | | | | Personal | | | | | | | | App | No effect |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | D | CA | C | R | An | DS | CC | PC | TD | M | Att | I | AC | Clb | F | IcA | S | | |
| Chen et al. (2019) [2] | ✓ | ✓ | | ✓ | | | | | | | | ✓ | | | | | | ✓ | AR-based Multidimensional Concept Maps | |
| Chien et al. (2019) [14] | | | ✓ | ✓ | | | ✓ | | | | | | | | | | ✓ | | n.d. | Performance Memorisation Comprehension |
| Chen (2020) [64] | ✓ | | ✓ | | | | | | | | | | | | | | | | AR game-based learning system | No difference |
| Wen et al. (2023) [65] | | | ✓ | | | | | | ✓ | | | | | | | | | | Plant Lifecycle AR | No difference |
| Weng et al. (2020) [7] | | | | | | ✓ | | | | | | ✓ | | | | | | | n.d. | Performance Memorisation Comprehension |
| Huang et al. (2022) [3] | ✓ | | | | | | | | | | | ✓ | | | | | | | n.d. | |
| Chang et al. (2016) [13] | | | ✓ | | | | | | | | ✓ | | | | | | | | ARFlora system | No difference |
| Wang et al. (2022) [15] | | | | | | | | ✓ | | | ✓ | | | | | ✓ | | | AR-based 3D e-book | Self-efficacy performance |
| Erbas et al. (2019) [66] | | | | | | | | | | | ✓ | | ✓ | | | | | | Developed for the study | No difference in performance |
| Arici et al. (2022) [4] | | ✓ | | | ✓ | | | | | ✓ | | | | | | | | | Developed for the study | |
| Karagozlu (2018) [67] | | ✓ | | | ✓ | | | | | | | | | ✓ | | | | | Aurasma* | |
| Keçeci et al. (2021) [9] | | ✓ | | | | | | | | | | | | | | | | | Anatomy 4D. | No difference in attitude |
| Fokides et al. (2018) [1] | ✓ | | | | | | | | | | | | ✓ | | ✓ | | | | Arloon's "The human body anatomy" | |
| Omurtak et al. (2022) [8] | ✓ | | | | | | | | | | | | | | | | | | n.d. | No difference in motivation |
| Özeren et al. (2023) [6] | | ✓ | | | | | | | | | ✓ | | | | | | | | CellAR ** | |

Note. A: learning; D: performance; CA: construction of learning/knowledge; C: comprehension; R: problem solving; An: analysis (Bloom's domain); DS: higher level performance; CC: decreases cognitive load; PC: critical thinking; TD: making decisions; M: motivation; Att: attitude; I: interest; Ac: self-control; Clb: collaboration; F: focus; IcA: interaction with the environment; S: satisfaction; *: app discontinued; **: Android system only; n.d.: not defined.

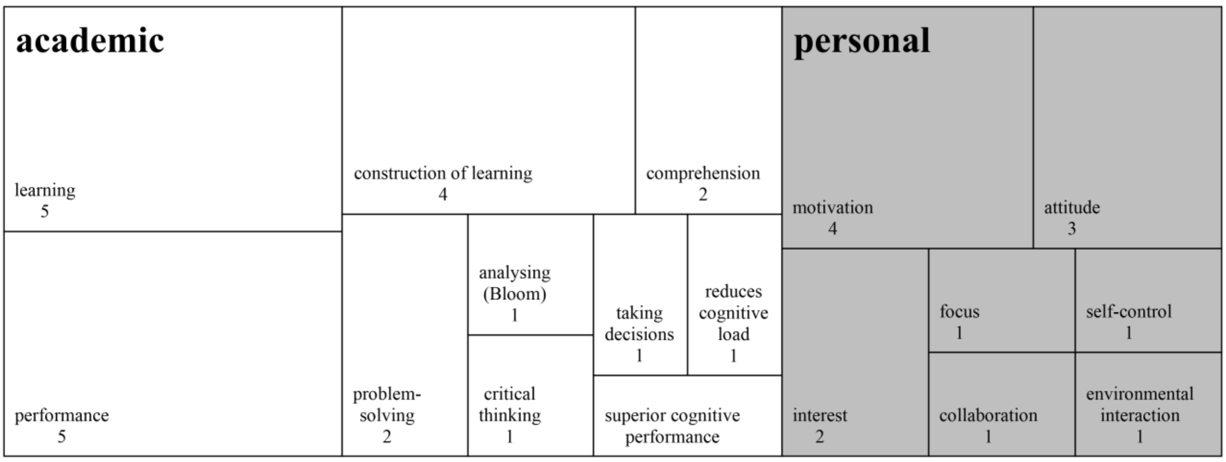


**Figure 8. Distribution in the dichotomy: cognitive/academic vs affective/personal, of the advantages of integrating AR into learning in the studies analysed**

The analysis of other publications mentions the same aspects considered in Table 11. The authors Arici et al. (2021) [78] in a case study designed to teach “Sun, Earth, and Moon”, “Solar System and Eclipses”, and “Solar System and Beyond”, perceive that when AR was integrated into the lesson that students were able to concretize abstract knowledge, the topics were easier to understand, and their motivation increased. Cheong et al. (2022) [79] in a quasi-experimental study with 103 high school students in the domain of cell structure, were only able to confirm that AR can increase students’ positive emotions towards learning. Deha et al. (2023) [23] in a study where AR was implemented with primary students for Solar System subject, confirmed the improvements of its use on the correctness of students’ performance. Shahrir & Emran (2023) [80] in a study about road safety with eight-year-old students, in Malaysia, confirmed advantages and positive outcomes as using this AR system enhanced children’s engagement, with easiness in comprehension and following instructions. Alkhasawneh & Khasawneh (2024) [19] in a study with 30 students with learning difficulties, divided into two 15-student classes, one control and one experimental, concluded the benefits of AR due to better performance of the experimental group as they were able to develop creative and imaginative thinking. Betsko et al. (2024) [81] in a study with students within military institutions, integrating AR into English Language Teaching and Information Technologies express the innovative aspect of AR and state that students are engaged in a meaningful, more immersive, and impactful learning experience, preparing students to better succeed in a digital world.

#### *3-3-2- Disadvantages*

Some authors reported not having found any positive and statistically validated effect on the use of AR compared to conventional teaching. The study developed by Chen et al. (2019) [2] was included in this category. The authors indicated no statistical results that show an advantage in the use of AR in students' performance in terms of memorization and understanding (domain of Bloom's taxonomy). The same happened in the study carried out by Weng et al. (2020) [7]. The studies of Chen (2020) [64], Wen et al. (2023) [65], Chang et al. (2016) [13], Wang et al. (2022) [15] and Erbas et al. (2019) [66], are in agreement in stating that there are no differences that justify the use of AR, an aspect that they assessed by analysing academic performance. Finally, Keçeci et al. (2021) [9] reported that there were no improvements in attitudes towards science or technologies and Omurtak et al. (2022) [8] did not record significant differences in motivation, adding that high levels of anxiety were generated in students who took exams. Regarding this aspect, Erbas et al. (2019) [66] reported that the absence of statistically significant differences was due to teaching centred on exams. Cheong et al. (2022) [79] on a quasi-experimental study with 103 high school students rejected, using a *t-test* analysis, the hypothesis of AR improving learning performance, as the authors could only confirm the impact of AR on academic emotions, as students refer satisfaction with the immersive experience. Shahrir & Emran (2023) [80] express as weaknesses the difficulty for students to hold their devices correctly while scanning the codes or trying to capture information.

### *3-4- Teaching Strategies Associated with the Application of AR*

In the strategies developed with students (Table 12), only the studies by Chen (2020) [64] and Chien et al. (2019) [14], analysed the use of AR outside the classroom context. All remaining studies took place in a classroom context. Chen (2020) [64] used AR in the context of a field trip after work carried out in class and Chien et al. (2019) [2] combined class work with the textbook and the use of AR to study the leaves outside the classroom. Among the teaching strategies described in the studies regarding the experimental group, the one where the use of AR occurred, the following stand out: the use of multidimensional concept maps [2], Inquiry-based learning [65], Project-based learning (Arici et al., 2022) [4], modified version of Bybee's 5Es model [1], slides with images [11], and textbook or e-textbook or teacher-created printed materials [3, 6-9, 15, 66, 67].

## 4- Discussion

The analysis of 15 studies revealed a strong effect size ($d$ = 1.13 [0.39;1.86]) on student learning for those who used AR compared to those who did not. However, AR cannot be considered entirely separate from the teaching strategies employed. Recent studies in other science areas also report effective results on student learning with AR-based instruction. For instance, Demircioglu et al. (2022) [82] found that an experimental group using an AR-based app to study the Solar System significantly outperformed the control group. Similarly, Setiawaty et al. (2024) [83] found that students in an experimental group using inquiry-based AR learning also outperformed the control group, particularly in the cognitive domains of understanding and knowledge. Ferrari et al. (2024) [22] concluded that AR-based instruction in a study of secondary education students in astronomy consistently led to better results than those of the control group, showing substantial improvements. These results were attributed to the positive impact of AR on academic performance.

Cao & Yu (2023) [36] reported a moderate effect size ($d$ = 0.85), supporting the hypothesis that learning achievements in AR-assisted education are significantly higher than those in non-AR-assisted education. For students from the millennial (born between 1981 and 1995) and Z generations (born between 1996 and 2012), AR was noted as an appropriate learning tool as it blends the real and virtual worlds. Santos et al. (2013) [84] are cited as stating that AR-based learning is an active method that aids the transfer of acquired information into long-term memory. AR is recognized as a rapidly expanding technology with strong potential in education across different levels and subject areas

[85]. However, the analysis does not clarify which teaching strategies yield the best results, as the majority of studies (53.33%, *n* = 8) involved traditional methods using textbooks, e-textbooks, or other printed material provided by the teacher. The duration of each intervention seems to influence the results, with better effect sizes observed in studies lasting four weeks or more, a trend noted in 40.00% (*n* = 6) of the studies with strong effect sizes. This finding aligns with Anil & Batdi (2023) [86], who conducted a meta-analysis of 55 studies in Science, Biology, and Physics, observing high effect sizes in studies focused on high school or secondary school students.

Regarding the applications used, four studies did not disclose this information [3, 7, 8, 14], while three studies integrated commercial applications. For example, Karagozlu (2018) [67] mentioned Aurasma (a discontinued app), Fokides et al. (2018) [1] referred to Arloon's Anatomy (available for iOS and Android), and Keçeci et al. (2021) [9] indicated Anatomy 4Kid (another discontinued app). Most studies (53.33%, *n* = 8) used applications developed specifically for the studies, with Unity and Vuforia being the preferred platforms, as noted by Koumpouros (2024) [46]. Conventional teaching methods, such as using textbooks or multimedia presentations, were the most common in the studies analysed. However, the study by Arici & Yilmaz (2022) [4] used Problem-Based Learning (PBL) as a teaching method, which set it apart from the others. AR may enhance student satisfaction and motivation regardless of the teaching method applied, potentially improving the learning experience and performance [36]. However, this could also increase the effort required from students during assessments, especially when solving real-world problems, due to AR's immersion and contextualization features, as suggested by Chang et al. (2022) [45]. Chen et al. (2019) [2] found that using augmented reality-based multidimensional concept maps was an effective learning approach, leading to better student performance compared to using traditional concept maps. The study by Fokides et al. (2018) [1] applied a modified version of the 5Es model, leading to better student engagement, improved collaboration, and enhanced learning outcomes. While AR generally produces positive results, four of the 15 studies analysed reported no significant differences in learning outcomes between students who used AR and those who did not. Continued research in this area is necessary, especially as AR technology becomes more accessible to students and teachers, particularly through mobile devices (smartphones).

**Table 12. Identification of the 15 studies for treatment in the experimental group vs control group and duration**

| Authors (date) | Experimental group | Control group | Duration |
|---|---|---|---|
| Chen et al. (2019) [2] | ARMCM (Augmented Reality-based Multidimensional Concept Maps) built with Vuforia. Unity and 3ds Max software. | MCM (Multidimensional Concept Map) | *n.d.* |
| Chien et al. (2019) [14] | Indoor class with traditional textbook and observation of leaf arrangement through AR. Outdoor leaf arrangement observation with AR. | Indoor class with traditional textbook and observation of leaf arrangement through herbarium. Outdoor leaf arrangement observation. | 110 min (15+40+40+15) |
| Chen (2020) [64] | Learning activity in field trip with reflection prompts and AR. | Learning activity with reflection prompts but without AR. | 2 weeks + 40 min + 1 week (field trip to learning park) + 40 min |
| Wen et al. (2023) [65] | Class learning with inquiry-based learning framework (QIMS) and AR integration on iPad. | Class learning with inquiry-based learning framework (QIMS) and iPads without using AR. | 3 weeks |
| Weng et al. (2020) [7] | Print book plus AR as a learning supplement | Print book | 90 min (20+5+45+20) |
| Huang et al. (2022) [3] | Learning materials with pictures and content. learning sheets plus AR | Learning materials with pictures and content. learning sheets | *n.d.* |
| Chang et al. (2016) [13] | Teacher used slides to teach the growth of plants. and then students used ARFlora system to strengthen their knowledge about the growth of plants. | Teacher used slides to teach the growth of plants. and then students watched a video to strengthen their knowledge about the growth of plants. | 180 min (120 learning fundamental + 60 strengthening) |
| Wang et al. (2022) [15] | Taught with AR and e-book to complete the learning project. | Taught with traditional PowerPoint-based (PPT-based) instruction and science textbook. | 180 min (3 × 60 min) |
| Erbas et al. (2019) [66] | Along with the content of the ninth-grade biology course curriculum. AR activities with tablets were carried out. | Students followed the standard. curriculum-based instruction programme. | 7 weeks |
| Arici et al. (2022) [4] | Problem-based learning (PBL) class supported by AR. | PBL class. | 8 weeks |
| Karagozlu (2018) [67] | Textbook and prepared sticker to place on it while relevant topic was being covered. The stickers triggered the animations on Aurasma (AR app). | Textbook and no AR. | 14 weeks |
| Keçeci et al. (2021) [9] | Anatomy 4D application was used in the experimental group: support and movement system. respiratory system. and circulatory system subjects. All the experimental group students used these applications in their school under the guidance of researcher. | Control groups. the current textbook was adhered to during the course processing process. | 8 weeks |
| Fokides et al. (2018) [1] | Taught with a slightly modified version of Bybee's 5Es model using tablets and an application. | Taught conventionally with students using a printed textbook. | 1 month (4 × 2h sessions) |
| Omurtak et al. (2022) [8] | Experimental application was made in the cell unit of the ninth-grade biology course. in classroom environment. Mobile AR application was installed on the phones and used by students; computers were also used by students in the experimental group. | Lessons in line with the current program. and the subjects were explained by the teacher. | 6 weeks |
| Özeren et al. (2023) [6] | Experimental group using developed AR for Android operating systems in addition to the regular course materials (textbooks. e-books. printed materials. videos. visuals. etc.). | Lessons using regular course materials (textbooks. e-books. printed materials. videos. visuals. etc.). | 4 weeks |

Note. n.d.: not defined.

## 5- Conclusion

This systematic literature review and meta-analysis examined 15 relevant studies that employed a quasi-experimental design and were published in peer-reviewed, indexed journals. The studies included were published after 2010. The first research question focused on the learning environments associated with the integration of AR in teaching Natural Science (NS) and Biology to primary and secondary school students aged between 5 and 18 years. In 11 of the studies, AR was integrated into conventional teaching contexts, primarily using textbooks (or e-textbooks), occasionally supplemented by multimedia presentations (such as PowerPoint or video) and AR markers. None of the studies provided a comparative analysis of educational environments with different teaching strategies associated with AR use. Notably, five studies were highlighted: one used AR with a multidimensional concept map, another combined AR with a field trip and observation outside the school, one integrated AR for observations inside the school, another utilized AR in inquiry-based learning, and one applied AR in problem-based learning.

The second research question addressed the effect of AR on student learning, revealing a strong effect size with a Cohen's d of 1.13 ($p$ = 0.00), with results ranging from -0.14 to 5.85. For the third question, concerning the impact of AR on students' motivation to learn, the global values from six studies showed a moderate effect size ($d$ = 0.52; [0.30;0.74]). The fourth question explored the advantages of integrating AR into NS and Biology teaching, identifying several benefits based on the categorization of terms used in the analysed articles. These advantages included improved learning, enhanced performance, better understanding, increased confidence in problem-solving, higher cognitive engagement (referencing Bloom's taxonomy), reduced cognitive load, and promoted decision-making and critical thinking. Additionally, AR was found to positively impact students' motivation, attitude towards learning or the subject, self-control, collaboration, focus, interest, satisfaction, and interaction with the environment.

For the fifth question, regarding the effectiveness of teaching strategies associated with AR use, no data was found in the 15 studies analysed to make a conclusive assessment. This highlights the need for further research to compare AR's effectiveness in various teaching strategies within the same school context, to better understand the impact of these variables on student learning outcomes and motivation. More research is needed at non-higher education levels, particularly in NS and Biology, and potentially in other subject areas, focusing on the integration of AR with different teaching methods. The availability of diverse, free AR apps accessible via smartphones presents an opportunity for integration into teaching and learning scenarios. Addressing technical challenges and fostering partnerships between students and teachers can enhance learning environments, allowing for the observation and analysis of phenomena that might otherwise be difficult to study.

## 6- Declarations

### *6-1- Author Contributions*

Conceptualization, A.F. and G.L.M.; methodology, A.F. and G.L.M.; formal analysis, A.F.; investigation, G.L.M.; resources, A.F. and G.L.M.; writing—original draft preparation, A.F. and G.L.M.; writing—review and editing, A.F. and G.L.M.; supervision, A.F. and G.L.M.; project administration, A.F. and G.L.M. All authors have read and agreed to the published version of the manuscript.

### *6-2- Data Availability Statement*

Data sharing is not applicable to this article.

### *6-3- Funding*

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### *6-4- Institutional Review Board Statement*

Not applicable.

### *6-5- Informed Consent Statement*

Not applicable.

### *6-6- Conflicts of Interest*

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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