The Educational Potential of XR Technologies in K–12 Learning Environments: A Systematic Review

Practitioner notes

What is already known about this topic

- XR (augmented, virtual, and mixed reality) can support learning by enabling immersive, interactive experiences that help students visualize abstract or otherwise inaccessible phenomena.
- Common challenges with integration of XR technologies into education include access and cost, teacher preparedness, technical constraints, classroom management demands, cognitive overload, and (for VR) potential discomfort for some learners.

What this paper adds

- It applies Education Taxonomy 4.0 to classify reported outcomes from XR studies into a common set of domains (cognitive, social, physical, self-regulatory, societal, and disciplinary), enabling more consistent interpretation across heterogeneous studies.
- It provides a structured overview of the K–12 XR evidence base (publication trends, country distribution, educational levels, sample sizes, study designs, and XR modalities), highlighting a predominantly quantitative literature with modest and variable samples.
- Evidence is concentrated in disciplinary, cognitive, and self-regulatory domains, with relatively limited attention to social, physical, and societal outcomes.
- Short-term improvements (particularly engagement/motivation and conceptual understanding) are more commonly reported than sustained outcomes, limiting confidence in durable and scalable effects.

Implications for practice and/or policy

- Educators should use XR where it adds unique instructional value (e.g., safe simulation, access to otherwise inaccessible phenomena) and align activities with explicit learning objectives and assessment.
- Policy and research agendas should prioritize shared outcome measures, minimum reporting standards, and longitudinal or multi-site studies that test sustained impact in real classrooms.

Abstract

Extended reality (XR) technologies represent an emerging field within educational innovation. This systematic review examines educational outcomes associated with the use of XR technologies, with special focus on augmented reality (AR), virtual reality (VR), and mixed reality (MR) in K–12 education. *Eligible studies were peer-reviewed, English-language journal articles that used systematic qualitative or quantitative methods to study learner outcomes related to XR in educational contexts.* The *Web of Science database was searched for* *publications from 2016 to 2024. From an initial pool of 279 records, 59 peer-reviewed studies were selected based on their focus on the impact of XR on educational outcomes. Findings were categorized according to the Education Taxonomy 4.0 framework, which includes cognitive, social, physical, self-regulatory, societal, and disciplinary domains of learning. Results indicated that XR technologies may have the potential to improve student motivation, engagement, and conceptual understanding, especially when paired with thoughtful pedagogical design. However, findings regarding long-term learning outcomes, knowledge retention, and scalability across diverse educational contexts were mixed, highlighting the need for further longitudinal and large-scale studies to evaluate sustained impact.*

Key words: *Extended reality (XR), augmented reality (AR), Virtual reality (VR), K–12 education, Taxonomy 4.0, systematic review*

Introduction

Digital technologies have become tightly integrated into everyday life, influencing how we communicate, work, and learn across nearly all areas of society. In education, digitalization has broadened access to learning opportunities and introduced new modalities for engagement. At the same time, it has intensified the demand for individuals to develop digital competences necessary to navigate, evaluate, and responsibly interact with digital environments for learning, employment, and civic participation (European Commission, 2023). DigCompEdu framework (Vuorikari et al., 2022) defines digital technologies as products and services that enable the electronic processing, sharing, and creation of information in digital form. Among these, immersive technologies are transforming how individuals learn, interact, and engage with information. Although these tools offer potential opportunities to support learning and engagement, their educational effectiveness is mostly dependent upon intentional and effective educational application (Godsk & Møller, 2025).

Traditional educational settings often struggle to sustain learner engagement when the material is abstract, theoretically complex, or lacks direct relevance to personal experience (Halverson & Graham, 2019). Extended reality (XR), which includes augmented reality (AR), virtual reality (VR) and mixed reality (MR), offers specific capabilities for designing interactive, three-dimensional learning environments that allow learners to explore abstract concepts, conduct virtual experiments, and engage with content in new and personalized ways (Sobota et al., 2020). Virtual reality (VR) immerses learners in fully synthetic environments, enabling them to simulate complex phenomena and explore places or processes otherwise inaccessible in traditional classrooms. Augmented reality (AR), in contrast, overlays digital content onto the real world, allowing learners to interact with layered information while remaining grounded in their physical surroundings (Furht, 2008). Mixed reality (MR) combines both approaches, enabling real-time interaction between virtual and physical elements. Empirical evidence increasingly suggests that XR technologies, when integrated into cohesive pedagogical frameworks, can improve conceptual comprehension, increase intrinsic motivation, and support active, exploratory learning (Fernández-Cerero et al., 2025). However, these benefits depend on careful instructional design, since inadequately integrated XR learning activities may lead to cognitive overload, fragmented attention, or shallow involvement. Adoption of XR technologies varies by education level: VR is primarily used in higher education, AR is more common in primary and secondary schools, and MR is less frequently across all settings (Huang & Tseng, 2025).

As these technologies gain visibility, interest is rising in their potential to meaningfully enrich K-12 education. In the U.S. context, K–12 education refers to the formal schooling from kindergarten (ages 5–6) through 12th grade (ages 17–18), covering both primary and seconday schooling (Khazaei et al., 2025). This phase forms the foundation for students' academic, social, and emotional development across core subjects such as language, arts, mathematics, science, social studies, and physical education (Yang et al., 2020; Zhang et al., 2022). While the structure of K–12 may vary globally, its central aim is to equip students with the skills and knowledge needed for higher education or entry into the workforce. XR is increasingly promoted by policymakers and educators as a tool to connect curricular content with real-world contexts, support creativity and collaboration, and respond to diverse learner needs. However, empirical evidence supporting XR's effectiveness in enhancing learning outcomes remains limited. A narrative review of 29 studies on the use of XR in K–12 education revealed that the majority were early-stage feasibility or design-focused investigations, primarily aimed at developing or proposing specific applications (Maas & Hughes, 2020). While such work is vital in an emerging field, few studies have systematically evaluated the impact of XR interventions on measurable learning outcomes, skills, or abilities. As a result, there is no clear synthesis of XR's effects across different technologies, research designs, or pedagogical goals in K–12 contexts. In addition, the lack of consensus on outcome measures further complicates comparison across studies and limits the ability to draw generalizable conclusions.

To address this gap, the present review adopts the Taxonomy of Education 4.0 as a framework for categorizing outcome measures related to XR use in K–12 education. This taxonomy conceptualiyes learning as a multidimensional model of human development encompassing cognitive, social, physical, self-regulatory, and societal domains (Tikhonova & Raitskaya, 2023). It is based on the idea that education should not only transmit knowledge but also develop a set of transferable competencies (abilities, skills, attitudes and values) that are essential for lifelong learning and adaptability in a rapidly changing world (World Economic Forum, 2023). Education 4.0 incorporates pedagogical approaches such as personalized and self-directed learning, inclusive access, problem-based and collaborative learning, and student-led lifelong learning. These elements are designed to support adaptability and learner agency across diverse contexts. The taxonomy bridges the gap between traditional education systems and future skill demands, offering a framework to help policymakers, educators, and stakeholders build adaptable, inclusive, and future-ready education systems (World Economic Forum, 2023).

Objectives

This systematic review investigates the educational outcomes associated with the use of extended reality (XR) technologies in K–12 education. Its central aim is to understand what outcomes of XR technologies have been documented in K–12 educational settings. To achieve this, the review investigates the following specific research questions: (1) How has the volume of XR-related research in K–12 education changed between 2016 and 2024? (2) Which countries have contributed most to XR research in K–12 contexts? (3) At which educational levels is XR most frequently studied? (4) What are the typical sample sizes in XR-related studies? (5) What methodological approaches are most commonly used? (6) What types of XR technologies (AR, VR, MR) are most frequently used? (7) Which Education Taxonomy 4.0 domains are most often addressed, and what are the outcomes?

Methods

The current systematic review employed the PRISMA 2020 statement, as outlined by Page et al. (2021), to assess and compare peer-reviewed literature on the use of XR technologies in educational environments. A search of the International Prospective Register of Systematic Reviews (PROSPERO) revealed that no similar systematic reviews on this topic were available.

Eligibility criteria

A protocol outlining the analysis methodology and inclusion criteria was developed in advance. To qualify for inclusion, studies had to meet the following criteria:

1. Investigate any aspect of learner outcomes related to the use of XR technology in educational contexts.
2. Present qualitative and/or quantitative data collected through systematic methods.

Only peer-reviewed journal articles were considered to ensure the use of high-quality and credible data. Systematic reviews identified through database searches were excluded. The selection was restricted to articles published in English between 2016 and 2024.

Exclusion criteria

Studies were excluded from the review based on the following criteria:

1. The study did not involve the use of extended reality technology (augmented reality, virtual reality, or mixed reality) as a core component of the intervention or research focus.
2. The study did not adopt a systematic empirical research design, such as qualitative, quantitative, or mixed methods approaches (e.g., conceptual papers, opinion pieces, or theoretical discussions without data were excluded).
3. The study's primary focus was not related to K–12 education or did not address educational outcomes in a formal learning context.
4. The study was not written in English.
5. The study was not a peer-reviewed journal article (e.g., conference proceedings, dissertations, reports, or grey literature).
6. The study was published prior to 2014.
7. Systematic reviews and meta-analyses were excluded to avoid duplication and maintain focus on primary research evidence.

In addition, records were excluded at various stages of the review process, including those automatically flagged as ineligible (e.g., duplicates, irrelevant titles/abstracts), records not retrievable in full text, and full-text reports excluded based on the above criteria.

Information sources

We conducted a search for papers that met the inclusion criteria. The initial search began in December 2024 and was updated in February 2025.

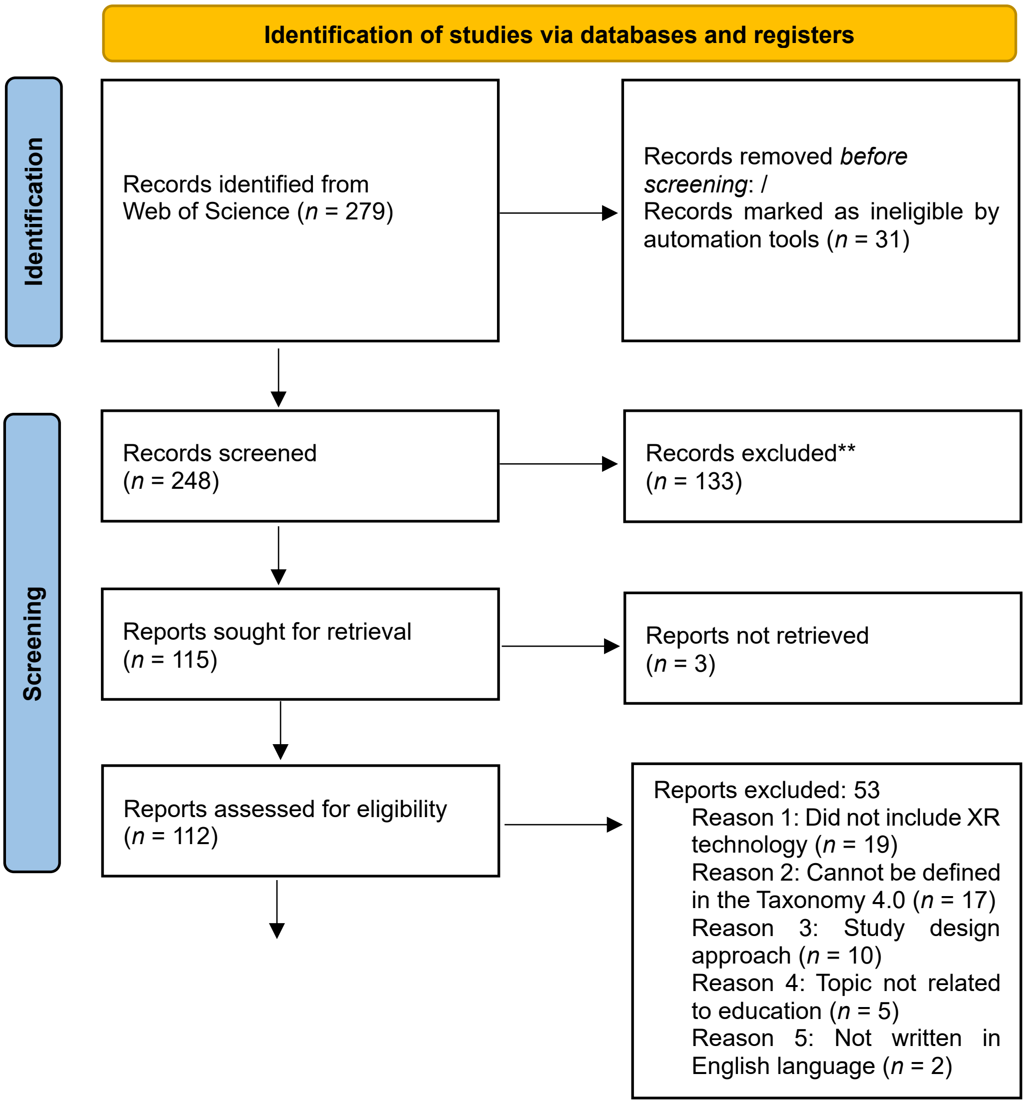
Search strategy

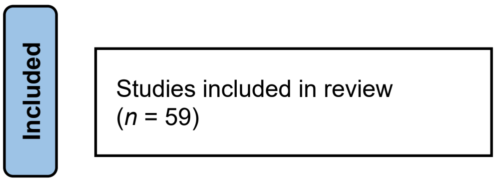
Initially, the most relevant keywords were identified through a preliminary search in the specified electronic databases: Web of Science, EBSCOhost Web, ProQuest Dissertations & Theses Global, ScienceDirect (Elsevier), Scopus, and SAGE Journals. These keywords were then used for a comprehensive search of the Web of Science database.

For Web of Science we used the advanced search interface and the search syntax: *(((((((AK=(xr)) OR AK=(extended)) OR AK=(ar)) OR AK=(augmented)) OR AK=(vr)) OR AK=(virtual))) AND (TS=(school) OR TS=(teacher) OR TS=(education) OR TS=(learning)) NOT (TS=(covid) OR TS=(university) OR TS=(higher) OR TS=(preschool) OR TS=(patient) OR TS=(nursing))) AND ((TS=(outcomes) OR TS=(effects))) AND (TS=(K-12) OR TS=(primary) OR TS=(secondary) OR TS=(elementary)) NOT (TS=(review) OR TS=(meta))*.

Selection process

Articles identified through the literature searches and reference list checks were imported into Zotero, and duplicates were removed. The team of 4 researchers independently reviewed the titles and abstracts of the first 50 records, resolving discrepancies through discussion until a consensus was reached. Subsequently, the authors evaluated all retrieved publications' titles and abstracts. In cases of disagreement, discussions were held to determine whether articles should proceed to full-text screening. Full texts of all potentially qualifying studies were obtained and independently reviewed by researchers. Any disputes regarding inclusion were resolved through debate to reach a consensus.





Data collection process

The initial search process from the Web of Science database generated 279 results. After removing duplicate entries and those flagged as ineligible by automated tools, a total of 248 articles remained for an initial screening. After a preliminary screening involving title, abstract assessment, and keywords, an additional 133 results were excluded. 3 articles were unavailable in full text and were subsequently removed from the study. A detailed review of the remaining 112 studies has been conducted and 53 additional studies were excluded after analysis of the full text. Among the reasons for exclusion were: 19 studies did not include XR technologies, 17 studies could not be defined in Taxonomy 4.0, 10 studies had inappropriate study design approaches, 5 studies were not related to education, and 2 studies were excluded because they were not written in English language. We included 59 studies in the final systematic review.

Data items

The following data were extracted from each included study: first author, year of publication, general construct or domain assessed, type of XR technology used (AR, VR, or MR), target age group of participants, sample population and country, sample size, mean age and standard deviation (where available), instruments used to assess outcomes, reported psychometric properties, statistical tests applied, and general findings related to XR implementation and effectiveness.

Synthesis methods

Eligibility for Synthesis

Full-text articles were retrieved and independently reviewed in full by the research team. Studies were eligible for synthesis if they reported on at least one measurement property of interest related to XR interventions in K–12 education. Eligibility decisions were based on the relevance of the constructs assessed, clarity of methodology, and comparability of target populations. When multiple studies examined the same measurement property for a similar construct, technology, or educational level, they were grouped for synthesis. In cases of overlapping data or closely related interventions, expert judgment was applied to determine inclusion to ensure coherence across synthesized findings.

Method of Synthesis

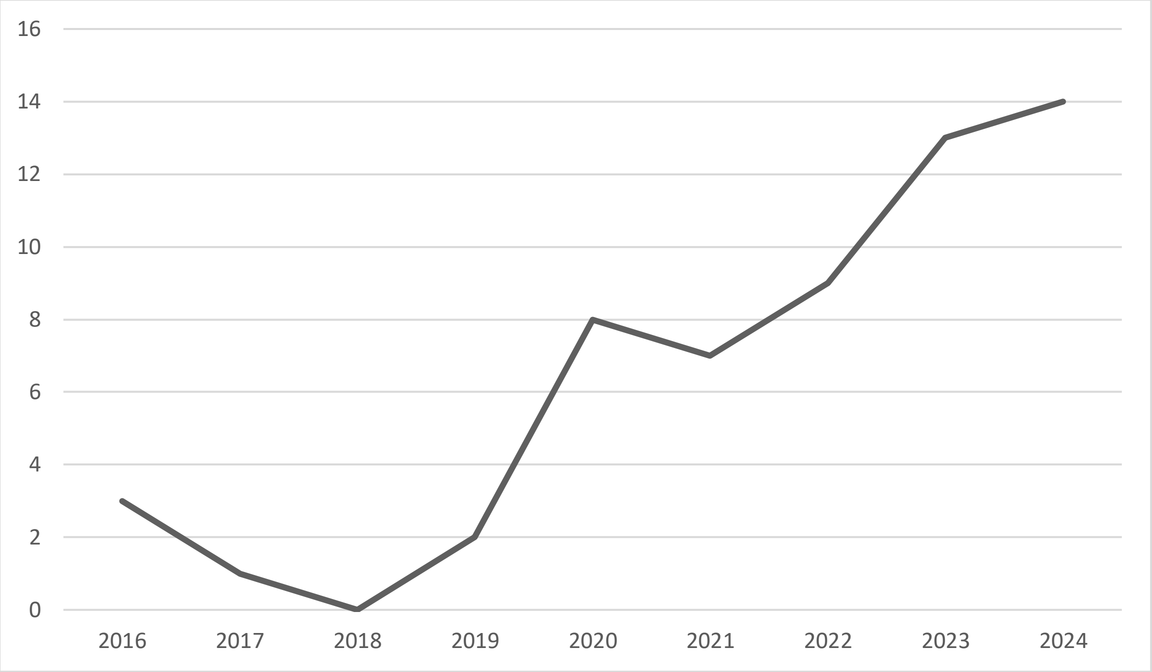
Each study was evaluated for its measurement properties. Ratings were assigned as either sufficient or not sufficient according to established criteria. Each team member independently assessed the reported properties. In cases of discrepancy or disagreement, a consensus meeting was held in which all relevant studies were re-evaluated by domain experts until agreement was reached. A qualitative synthesis was then constructed for each measurement property by aggregating findings across studies. Inconsistencies were discussed and, where possible, explained based on differences in methodology, sample characteristics, or instrument design. No meta-analyses were performed due to heterogeneity in study designs, measurement tools, and reported outcomes.

Results

Table 1 presents the number of studies by year and country where the studies were conducted. Between 2016 and 2018, a total of 4 research studies were published, with no publications record in 2018, marking it as the only year in the dataset without any studies among all the years reviewed. From 2019 onwards, a consistent upward trend in the number of publications is observed, beginning with 2 studies in 2019 and growing steadily through 2020 (*N* = 8), 2021 (*N* = 7), and 2022 (*N* = 9). The number of publications reached its peak in 2023 and 2024, with 27 studies published, representing nearly 46% of the total sample (*N* = 59). The data on the Figure 1 indicates a marked growth in scholarly interest in the field, particularly from 2020 onwards. The results of the analysis indicate that the studies are more concentrated in recent years and not in a single period but have gradually increased over time.

Figure 1

Number of studies (N) by year of conducted studies



Research on the use of XR technologies in education is geographically unevenly distributed. The reviewed studies were conducted in 18 different countries (Table 1). The highest number of studies was conducted in Taiwan (*N* = 14), followed by China with three fewer studies (*N* = 11). Turkey (*N* = 6), and Greece (*N* = 5) together contributed 11 research studies. Furthermore, Spain (*N* = 4), and United States (*N* = 3) together contributed 7 research studies. A collective group comprising Singapore, Indonesia, Saudi Arabia, and South Korea accounted for an additional 8 studies. While the remaining countries (Malaysia, Ireland, Iran, Bulgaria, Kazakhstan, Cyprus, Croatia) contributed an additional 8 research studies.

Altogether, the top four most represented countries (Taiwan, China, Turkey, and Greece) produced more than half of all reviewed studies (*N* = 36). Other countries were represented to a much lesser extent, with most countries (*N* = 12) contributing only one or two studies between 2016 and 2024. These findings suggest that while international interest in the field is growing, research activity remains heavily concentrated in specific countries.

Table 1

Number of conducted studies (N) by country

Country of publication		
Country	*N*	*Total*
Taiwan	14	14
China	11	11
Turkey	6	6
Greece	5	5
Spain	4	4
United States	3	3
Singapore	2	2
Indonesia	2	2
Saudi Arabia	2	2
South Korea	2	2
Malaysia	1	1
Ireland	1	1
Iran	1	1
Bulgaria	1	1
Kazakhstan	1	1
Cyprus	1	1
Croatia	1	1
Iraq	1	1
Total	59	

Furthermore, we present studies based on the size of the research sample and the level of education at which the study was conducted. As evident from Table 2, the largest number of studies (*N* = 39) are aimed at exploring the use of XR technologies among primary school students. Secondary education was addressed in 17 studies, meaning that less than a third of the research focuses on secondary school students. Only three studies simultaneously investigated the effectiveness and impact of XR technologies in education across both primary and secondary school student samples. This highlights the limited number of studies addressing the transition and comparisons between these two levels of education.

Table 2

Number of studies (N) by level of education

Type of education		
Primary education	Secondary education	Both
39	17	3

Regarding sample size, we find that the average number of participants in the research sample was 89.61 (*SD* = 87.46). The range of sample sizes was very wide, with the smallest study including only 3 students (Gulboy & Denizli-Gulboy, 2024), while the largest study involved as many as 500 students (Delgado-Rodríguez et al., 2023). While some studies involved small samples, others included significantly larger groups (Table 3), which may influence the generalizability of findings. This variation in sample size also suggests differences in research scope and design across studies, which should be taken into consideration when interpreting the outcomes related to XR technology use in educational settings.

Table 3

Number of studies (N) by size of the research sample

Size of the research sample		
≤ 50	50 > 100	≥ 100
21	20	18
$M = 89.61$ $SD = 87.46$		
$N = 59$		

Table 4 presents the distribution of studies by methodological approach. Most of the reviewed studies ($N = 35$) employed quantitative approach, indicating a strong preference for quantitative data-driven analysis in XR-related educational research. Mixed-methods study designs were also prominently used ($N = 22$), reflecting an effort to integrate both numerical and contextual insights. In contrast, only a small number of studies ($N = 2$) adopted a purely qualitative approach, suggesting limited exploration of in-depth experiential perspectives.

Table 4

Number of studies (N) by type of research study design

Study design			
Quantitative	Qualitative	Mixed	Total
35	2	22	59

The analysis of XR technologies used in the reviewed studies shows that augmented reality (AR) was the most frequently investigated in an educational context, appearing in 35 studies (Table 6). Virtual reality (VR) was investigated in 24 studies. The effect of mixed reality (MR) was examined in only one study.

Table 5

Number of studies (N) by type of XR technology

Type of XR Technology			
VR	AR	MR	Total
24	35	1	59

The reviewed articles were categorized into six domains aligned with the Taxonomy 4.0 (Tikhonova & Raitskaya, 2023; World Economic Forum, 2023). Most studies focused on disciplinary knowledge, with 32 studies addressing this domain (Table 7). This is followed by studies examining cognitive skills and engagement ($N = 19$). Nineteen studies explored the effects of XR technologies in education on self-regulation. The social effects of XR technologies were investigated in 5 studies. Even fewer studies focused on broader societal effects of XR technologies ($N = 3$). Physical effects were the least studied, with just one article addressing this domain ($N = 1$). The analysis of the reviewed studies on XR technologies in education reveals a clear predominance of research in the domains of disciplinary knowledge, followed by cognitive effects and self-regulatory effects, indicating a strong focus of XR technologies on enhancing individual learning.

Table 6

Number of studies (N) by field according to the taxonomy of objectives

General fields/domains according to Taxonomy 4.0					
Cognitive	Social (inter – personal)	Physical	Self-regulatory	Societal (extra – personal)	Disciplinary knowledge
19	5	3	20	3	30

The studies analyzed in this review address a broad spectrum of topics related to the effectiveness and impact of XR technologies within K–12 education.

Knowledge and information

Disciplinary knowledge

The effect of XR on disciplinary knowledge was examined across four subject areas: science, mathematics, language, and social science.

Augmented and virtual reality technologies have been investigated as means for improving science instruction, especially for understanding concepts and subject matter**.** Petrov & Atanasova (2020) and Volioti et al. (2022) proposed that interactive AR/VR experiences could improve students' understanding of scientific concepts. Their findings suggest that certain educators view immersive technology as capable of supporting the instruction of complex content and that it could promote the acquisition of domain-specific knowledge in STEM education. Hung et al. (2024) similarly found that elementary students using online collaboration scripts during VR-based STEM activities showed greater competence in sustainable ecology and environmental science. Two other studies also suggested that integrating AR with concept mapping may support disciplinary learning in science education (Chen et al., 2016; Chou et al. 2022). For example, Chen et al. (2016) reported that combining AR with concept maps appeared to improve elementary students' understanding of food chains by facilitating more structured knowledge organization. The validity of these claims is constrained by methodological limitations, and their results have not yet been widely replicated across diverse educational contexts.

Several articles included in the review show that virtual and augmented reality could help students understand abstract scientific concepts like celestial mechanics, electric circuits, and weather systems by making learning more interactive and immersive (Hung et al., 2024; Hwang et al., 2016; Liu et al., 2022; Winarni et al., 2024). For instance, students who played an AR-based game about butterfly ecology achieved higher post-test scores on this topic, indicating improved conceptual understanding (Hwang et al. 2016). Liu et al. (2022) reported that fourth grade students participating in immersive VR science lessons, featuring visually rich content on weather phenomena and the human respiratory and digestive systems, showed improved comprehension of abstract topics within the studied domain. Delgado-Rodríguez et al. (2023) found that immersive virtual laboratories may support students' engagement with scientific experiments, such as cell observation, potentially fostering deeper conceptual understanding through interactive simulations. Although these studies highlight the potential instructional applications of XR, the existing evidence remains preliminary, with Chen (2020) and Delgado-Rodríguez et al. (2023) reporting limited effects on disciplinary learning outcomes in science. Namely, Chen (2020) showed that elementary students learning about insect-related content in a context-aware AR environment did not show significant gains in science knowledge compared to traditional methods. The evidence suggests that XR is not universally effective and must be carefully adapted to specific learning environments.

In addition to studies focusing on general student populations, a small number of investigations have explored the use of immersive technologies teaching science to students with specific learning needs. Gulboy & Denizli-Gulboy (2024) reported that AR-based instruction was associated with improvements in conceptual understanding of science topics among secondary students with intellectual disabilities. Similarly, Zhang & Su (2024) demonstrated that immersive virtual labs enabled students to better engage with scientific experiments (e.g., observing cells), supporting deeper conceptual understanding through realistic, hands-on simulations. These studies suggest potential benefits of XR in targeted contexts, though their findings remain exploratory and call for replication in larger and more diverse samples.

In mathematics education, XR tools have been explored primarily for their potential to enhance the teaching of complex or abstract topics. Shi et al. (2019) reported that a game-based immersive VR environment integrating quadratic functions into a basketball context improved seventh-grade students' math achievement and learning motivation. Similarly, Saundarajan et al. (2020) found that using the AR-based Photomath app significantly improved lower secondary students' performance in algebra and supported independent learning and problem-solving. In geometry, several studies found that AR applications can aid students' understanding of geometric solids (Cetintav & Yilmaz, 2023; Arvanitaki & Zaranis, 2020) spatial relationships, and 3D visualizations (Beisenbayeva et al., 2024). Akman & Cakir (2019, 2020) also observed performance gains in fractions through a VR game, while Gün & Atasoy (2017) found that although students using AR with 3D object demonstrated learning gains from pre- to post-test, between-group differences were not statistically significant. These findings should be interpreted with caution, as many of the studies rely on small samples, short intervention periods, or limited experimental controls, making it difficult to draw firm conclusions about the broader effectiveness of XR in mathematics education.

In language education, XR technologies have primarily been applied to support vocabulary acquisition, grammar comprehension, and oral communication, though their effectiveness appears to vary across contexts and task types. Some studies have reported improvements in English vocabulary acquisition through AR- and VR-based instruction, including gains in reading comprehension and vocabulary-picture matching (Hussein et al., 2023; Lai & Chang, 2021). Similarly, Liao et al. (2024) reported that the StemUp AR game enhanced fourth-grade English as a Foreign Language students' vocabulary, speaking, and listening skills. Çetin & Ulusoy (2023) found that AR improved third-grade students' oral retelling skills, attributing the gains to the engaging features of 3D characters and sound effects. However, not all studies showed clear advantages of XR over traditional education. Belda-Medina & Marrahi-Gomez (2023) and Marrahi-Gomez & Belda-Medina (2024) reported no significant differences in grammar or vocabulary outcomes between AR-enhanced and conventional lessons. Results in this area have been inconsistent, with positive outcomes reported in some cases and negligible effects in others.

The application of XR in social science education has primarily focused on enhancing historical understanding and spatial skills. Lázaro Carrascosa et al. (2024) reported that combining AR with game-based learning improved students' understanding of historical chronology and increased motivation through enhanced curiosity and enjoyment. Ventoulis & Xinogalos (2023) reported that although there were no performance gains from the AR game "The Gods of Olympus", the game enhanced student engagement, enjoyment, and perceived educational value in learning Greek mythology. Christopoulos et al. (2024) found that immersive VR supported learning in historical subdomains like architecture and political history, though it was less effective in conveying abstract temporal concepts. In contrast, Iasha et al. (2023) reported that field trip-based virtual reality (FVR) improved the cultural literacy of elementary school students, enabling deeper engagement, better understanding, and a greater ability to analyze and apply cultural knowledge compared to traditional video learning. Overall, the findings in this domain remain varied, with outcomes differing across subject focus, XR formal, and instructional approach.

Across disciplines, XR technologies have been explored for their potential to support disciplinary learning, with some studies reporting gains in conceptual understanding, engagement, and motivation. Positive outcomes have been observed in science, mathematics, language, and social science contexts, particularly where XR is used to visualize abstract content or support interactive tasks. However, findings remain inconsistent, and evidence of clear learning advantages over traditional methods is limited. Many studies rely on small samples and short-term interventions, restricting the generalizability of results. At present, the conditions under which XR meaningfully supports domain knowledge acquisition remain insufficiently understood.

Abilities and skills

Cognitive (analytical)

The three primary outcome measures examined in this category were *cognitive load*, *cognitive engagement*, and c*ognitive abilities,* as these themes emerged most consistently across the reviewed studies. Cognitive Load Theory states that cognitive overload arises when the demands of a learning task exceed the limited capacity of working memory (Sweller et al., 2019). Building on this, the Cognitive Affective Model of Immersive Learning suggests that excessive cognitive load can hinder learning outcomes (Makransky & Petersen, 2021). Cognitive engagement refers to students' mental effort and focus during learning. However, it often overlaps conceptually with constructs such as learning effectiveness and motivation (Fredricks et al., 2004). According to (Makransky & Petersen, 2021), effective instructional design of XR should aim to reduce unnecessary processing (extraneous cognitive load) while enhancing learners' cognitive engagement. Cognitive abilities encompass core mental processes such as memory and attention. These are especially relevant for XR interventions with children, as XR can create digital environments that mimic real-life situations, giving children opportunities to practice and strengthen the cognitive skills needed to handle these challenges. Nevertheless, most studies in this review focused on how XR affects students' cognitive load and engagement, while relatively few examined its impact on cognitive abilities.

Cognitive Load

In our sample, two studies found no significant increase in self-reported cognitive load when using VR compared to standard instruction (Liu et al., 2022; Xie et al., 2023). On the other hand, Yang et al. (2021) reported that students in AR-based learning environments experienced higher cognitive load than those using traditional instructional models. Increased cognitive load compared to traditional online learning was also reported by Zhang et al. (2024). Nevertheless, since students who learned through vicarious experience, that is, observing an instructor's demonstration and explanation in VR, showed significantly higher immediate knowledge acquisition than those in traditional online conferencing classes, the authors concluded that increased cognitive load in VR may not be an issue as long as its design is aligned with learning goals.

Two studies in our sample approached cognitive load from a different perspective: they investigated how different XR design elements affect cognitive load by comparing variations of XR-based interventions. According to Chou et al. (2022), AR-related cognitive load can be reduced by introducing multidimensional concept maps to help organize science-specific knowledge. Similarly, Li et al. (2023) showed that incorporating instructional textual cues in a VR environment did not raise cognitive load, yet it significantly enhanced learning performance and the development of mental models. Overall, the effects of XR on cognitive load are mixed and likely highly dependent on the design of individual XR papplications or services. However, the importance of carefully designing XR applications to avoid overloading students' working memory and attentional resources is unquestionable. To achieve an optimal level of cognitive load, a key recommendation is to incorporate features such as self-paced progression and adaptive learning mechanisms that respond to individual learner needs.

Cognitive Engagement

XR has the potential to improve cognitive engagement compared to traditional teaching because it offers immersive, interactive experiences that actively involve students in the learning process. Indeed, four studies reported higher cognitive engagement in XR methods compared to traditional instruction. For example, Ai-Jou et al. (2024) found that participants in the treatment group, who engaged with an AR-based educational game, showed significantly higher self-perceived learning effectiveness compared to a control group that interacted with a traditional board game. Similarly, Wen (2021) reported that an AR game designed to support Chinese character learning enhanced students' cognitive engagement, as measured through video-based observation methods. In another observational and qualitative study, students involved in AR learning activities showed higher cognitive and overall engagement, with fewer signs of disengagement, compared to those using multimedia-based lessons Drljevic et al. (2022), and similar findings were reported for immersive VR by Lee et al. (2024).

In contrast, Akman & Cakir (2020) found no evidence of a significant difference in self-reported cognitive engagement between a treatment group that played a mathematics-based VR game and a control group. In a study comparing traditional paper-based instruction, AR, and VR for teaching a foreign language, there was no significant difference in learning motivation and performance among the three groups (Hung et al., 2023). Likewise, spherical video-based virtual reality did not appear to promote students' cognitive engagement compared to a control group (Chen et al., 2024). In conclusion, while four studies reported higher cognitive engagement in XR learning environments, three studies found no significant differences, highlighting the need for further research to better understand the conditions under which XR can enhance cognitive engagement.

A key methodological limitation of studies examining cognitive load and cognitive engagement is their reliance on self-reported measures of cognitive load, rather than objective metrics. Additionally, most assessments were conducted post-intervention, offering limited insight into learners' cognitive processing during the actual learning experience. This underscores the need for more rigorous research designs that incorporate real-time and objective measures to capture cognitive load and engagement at pre-test and post-test, or as it unfolds during XR-based learning.

Cognitive Abilities

As stated previously, a limited number of studies have examined the effects of XR interventions on cognitive abilities. Due to the feasibility nature of most of these studies, methodological drawbacks are common, such as reliance on self-report measures of cognitive ability, the absence of control groups, or a lack of baseline performance assessments. For example, Wu et al. (2021) tested the effectiveness of spherical video-based VR and showed that the technology enhanced students' self-reported analytical problem-solving abilities compared to a control group that was exposed to common teaching practices. While Baumgartner et al. (2022) demonstrated that the consumption and production of XR videos improves students' spatial reasoning ability compared to pre-test, this study did not include a control group. In another study, a geometry-focused AR app significantly improved students' spatial relationships, 3D visualization, and understanding of geometry compared to traditional teaching methods. Yet these findings are based solely on post-test comparisons, with no pre-test data to establish baseline performance (Beisenbayeva et al., 2024). In the context of physical education, a VR-based soccer intervention was compared to traditional instruction on a playground (Lee & Lee, 2021). Students who took part in the VR intervention showed higher levels of confidence, concentration, and flow compared to those who attended traditional instruction. This study relied on self-reported measures, which may be subject to bias or inaccuracies in students' perceptions. Finally, Cai et al. (2022) conducted a study in which they combined AR with a brain-computer interface (BCI) - a portable electroencephalogram that measured electrical patterns generated by neural activity in the brain. Specifically, a BCI-based AR tool, designed to provide students with real-time feedback on their concentration levels, was compared to a control group who used AR without a BCI. The results showed that the BCI-based AR tool improved students' self-reported mental flow while not affecting their cognitive load compared to the control group.

Four studies in our sample focused on examining the effects of XR interventions on cognitive abilities of neurodiverse children in an educational context. In a small-scale pilot study, Tabrizi et al. (2020) found that a VR intervention significantly improved short-term memory (i.e. digit span performance) in children with attention-deficit/hyperactivity disorder (ADHD) compared to a passive control group. However, further research with a larger sample size and a broader range of cognitive assessments is needed to validate these findings. On the other hand, a pilot study by Tosto et al. (2021) found that incorporating AR into a web-based literacy program for children with ADHD did not significantly enhance literacy skill acquisition compared to the same program without AR. A study involving a small sample of children with learning disabilities provided preliminary evidence supporting the effectiveness of AR in enhancing reading comprehension skills (Shaaban & Mohamed, 2024). Finally, Wuang et al. (2021) focused on children with developmental delays, who were assigned to two groups: one group received AR-based training designed to enhance visual motor integration and visual perceptual function, while the other group received traditional visual perceptual training, both of which were administered by occupational therapists. The AR group showed improved visual-motor integration and visual perceptual skills compared to the control group. These findings suggest that XR-based training may hold promising clinical applications; however, its effectiveness in educational settings remains inconclusive due to the limited number of studies.

One study that did not fit into any of the subcategories described so far explored whether individual differences in cognitive abilities can impact students' engagement with VR-based learning tools. Results showed that students who have a better understanding of spatial rotation and angular geometry are more likely to report greater perceived control, and less distraction, when using VR technologies (Hite et al., 2019).

In summary, mixed effects were found for the effect of XR on cognitive load, cognitive engagement, and cognitive abilities. Methodological limitations, such as reliance on self-report measures, lack of control groups, and limited sample sizes, preclude drawing definitive conclusions at this stage.

Social (inter-personal)

Few studies explored how different XR technologies can enhance social skills, such as collaboration, communication, and negotiation in educational settings. Yang et al. (2021) reported that AR-based learning environments have the potential to support peer interaction and group cooperation. They conducted a group interview with six primary students after lessons involving Experience–Inquiry–Application (EIA) guided AR science activities and found out that students experienced more opportunities for hands-on work and personalized observation. Students felt that the EIA-guided activities gave them more time for group cooperation and communication.

Another positive influence of XR on collaboration was echoed in the findings of Beyoglu et al. (2020), who showed that mixed reality applications significantly increased primary students' motivation for collaborative work in science education. Although no significant differences were found in overall motivation for communication and participation, the experimental group demonstrated higher motivation related to collaboration. Beheshti et al. (2024) offered a more nuanced look at collaboration within AR-supported engineering design. Their study highlighted how students working in dyads negotiated technology ownership while visualizing ideas and communicating. Despite the use of collaborative language, post-interview reflections revealed that such expressions often masked an absence of true cooperation. Overall, findings of their study underscored the complexity of collaboration in AR contexts, influenced by interpersonal dynamics, attitudes, and prior experiences.

Finally, Hung et al. (2024) examined how scripted online collaboration in VR-supported co-creation tasks impacted communication during distance learning. Using pre- and post-test questionnaires, they found a significantly greater improvement in communication skills in the group that engaged with structured collaboration scripts, emphasizing the role of pedagogical design in enhancing virtual teamwork. It is important to note that most of these findings were based on very small samples, which limits the extent to which the results can be generalized.

Physical

Among the reviewed literature, just three studies explicitly focused on the physical domain. One study utilizing an Augmented Reality–based Kinesthetic Game-Based Training System (KBTS) reported statistically significant improvements in visual-motor integration, visual perception, adaptive behaviors, and school-related functions, compared to a control group using traditional training methods. KBTS was particularly effective in tasks requiring gross motor activities and real-time feedback (Wuang et al., 2021). Similarly, Lee & Lee (2021) found that students in VR-based soccer classes demonstrated significantly higher confidence and concentration than those in traditional physical education, suggesting that VR can enhance motivation and understanding in physical education through realistic simulations and personalized feedback. Amprasi et al. (2022) demonstrated that both immersive VR exergames and traditional training significantly improved selective attention in children aged 8–10 during volleyball-related tasks, with sustained effects over time; however, no significant difference in effectiveness was observed between the two methods.

Attitudes and values

Self-regulatory (intra-personal)

XR technologies are frequently associated with increased learner motivation, engagement, and positive attitudes toward learning. Zhang et al. (2024), Cetintav & Yilmaz (2023) and Liu et al. (2022) reported that students who interacted directly with VR environments reported higher levels of motivation and satisfaction than those in traditional learning settings. Alenezi (2023) observed that AR implementation based on the Attention, Relevance, Confidence, and Satisfaction (ARCS) framework significantly improved student motivation, while Chang et al. (2016) found that the ARFlora tool increased both motivation and long-term knowledge retention compared to video-based instruction. In the context of English language learning, Liao et al. (2024) reported that an AR game-based intervention improved English performance and motivation, particularly among rural students. Hwang et al. (2016) found that students who used an AR-based competitive game expressed more positive attitudes towards learning than those in a non-gamified AR condition. Similarly, Liu et al. (2022) described an AR package combining an app and a social game increased motivation alongside progress toward learning goals. Finally, Akman & Cakir (2020) reported that students engaging with a VR mathematics game “Keşfet Kurtul” demonstrated sustained enthusiasm and engagement in mathematics compared to those in the control group. However, most of these studies relied on short-term interventions and self-report data, limiting the extent to which these motivational effects can be generalized.

Some studies have explored how XR learning environments may influence students’ self-perceptions as learners, including confidence, academic self-efficacy, and engagement. Belda-Medina & Marrahi-Gomez (2023), Marrahi-Gomez & Belda-Medina (2024) and Tsai (2020) reported that students in AR-supported lessons reported greater engagement, more positive attitudes toward learning, and increased confidence. Hung et al. (2023) found that VR-based learning materials supported learners in expressing ideas more accurately and contributed to higher self-confidence and stronger sense of achievement. Other studies noted higher levels of concentration, perceived flow, and intrinsic motivation among students in virtual environments compared to those receiving traditional instruction (Lee & Lee, 2021), as well as gains in academic self-efficacy, satisfaction, and performance (Xie et al., 2023). There is also some indication that students responded positively to the inclusion of VR in classroom settings and were more cognitively engaged during instruction (Hui et al., 2022). The extent to which these reported effects reflect lasting changes in learners’ self-perceptions remains unclear.

A limited number of studies have investigated whether XR technologies can support strategic engagement, self-efficacy, and collaborative knowledge building. Wen et al. (2023) investigated the inquiry-based learning framework (QIMS), with and without AR, and reported improvements in students’ creative thinking, self-directed learning and critical thinking compared to the control group. One study used an AR-based brain–computer interface tool to support student engagement during open-ended science tasks, reporting improvements in students' perceived self-efficacy and ability to remain focused during inquiry-based learning (Cai et al., 2022). Other approaches have combined XR with interdisciplinary pedagogical models: the STEAM-6E framework, integrated with VR instruction, was associated with increased student motivation and creativity in project-based learning (Lin et al., 2023). In the context of disaster prevention education, an AR supported instructional tool was used to compare two collaborative learning formats. Both the board game and brainstorming conditions supported learning and motivation, although the board game group demonstrated more consistent improvements in collaborative knowledge building (Lu et al., 2022). Reported benefits remain speculative, given the exploratory nature and design weaknesses of most studies in this area.

Societal (extra-personal)

Only three studies have investigated how XR technologies might support societal or extra-personal learning goals in education. All three focused specifically on sustainability-related outcomes. One study compared an AR based game aligned with the Sustainable Development Goals to a traditional board game and reported that students in the AR group demonstrated higher achievement on sustainability topics (Ai-Jou et al., 2024). Similarly, a VR based STEM project involving collaborative exploration of environmental issues such as the polar regions and rainforests was found to increase students' awareness and knowledge of ecological protection (Hung et al., 2024). In a smaller qualitative study, students participated in an AR-supported engineering design activity that included visualizing three dimensional representations of sustainable cities. Results suggested that such experiences may support students in developing more nuanced understandings of sustainability concepts (Beheshti et al., 2024). The limited number of studies, modest methodological designs, and inclusion of primarily small-scale or qualitative approaches make it difficult to draw firm conclusions about the broader educational value of XR for supporting societal learning goals.

Discussion

XR technologies are gaining increasing popularity in K–12 classrooms, with many educators and researchers suggesting they hold transformative potential for teaching and learning. The goal of this review was to examine the extent to which these claims are supported across disciplinary knowledge, cognitive, social, physical, self-regulatory, societal domains.

XR-related research in K–12 education increased continually between 2016 and 2024, with a notable increase in 2020. Taiwan, China, Turkey, and Greece were the leading contributors, accounting for over half of all studies. Although there was a lot of variance, the majority of research focused on primary school and had an average sample size of roughly 90 participants. The majority of the studies employed quantitative designs, followed by mixed-methods, and qualitative designs. AR was the most extensively researched XR technology, followed by VR. MR was investigated in just one study.

Most studies were categorized into the disciplinary knowledge domain. This focus is expected, as disciplinary knowledge represents the most specific form of learning transfer (i.e., near transfer) and is of particular interest to educators seeking effective ways to explain complex topics and engage students more deeply in subject matter. Across science, mathematics, language, and social studies, XR was primarily used to support understanding of abstract or complex content. Studies in science education reported improved comprehension when XR enabled students to simulate systems or conduct virtual experiments, particularly in biology and environmental science. In mathematics, XR appeared to support learning in geometry and algebra by making symbolic and spatial relationships more accessible. Language learning studies often targeted vocabulary acquisition and speaking skills, with mixed results, while social studies applications focused on increasing learner interest in historical and geographical topics. Although positive effects were observed in each subject area, they were not uniform.

In the cognitive domain, most studies focused on examining the effect of XR on cognitive load and cognitive engagement. Effects on cognitive load varied considerably, with some studies reporting increases and others finding no significant difference from traditional methods. Cognitive engagement was more consistently positive but typically measured through post-task self-reports. Few studies examined objective changes in cognitive abilities, and those that did often lacked rigorous design.

In the self-regulatory domain, XR was frequently associated with increased motivation, confidence, and satisfaction, particularly in gamified or collaborative environments. The social domain was addressed in a limited number of studies, which suggested that XR may support collaboration and communication when integrated into well-structured group activities. The physical domain had even fewer studies, reporting potential benefits for visual-motor skills, attention, and movement-based learning. The societal domain was the least developed, with limited evidence suggesting that XR might support awareness of sustainability or civic issues through exploratory and project-based experiences.

The evidence base on XR in K–12 education points out several gaps in study quality. Most studies focused on AR, while VR was somewhat less common and mixed reality MR was addressed in only one study. This uneven distribution across XR modalities limits the ability to compare their relative effectiveness or suitability for different learning contexts. Similarly, there was a clear concentration of research in the disciplinary and cognitive domains, with relatively few studies focused on physical, societal or social outcomes. Longitudinal research was almost entirely absent, and very few studies included follow-up measures or comparisons across diverse school settings, populations, or curricular goals. As a result, the current literature provides limited insight into the sustained impact of XR or its effects across learner groups and educational contexts.

Despite some studies reporting positive effects on different aspects of learning, the overall findings of this review were mixed, and in some cases inconclusive. Several factors may account for this variability. First, a large number of studies employed short-term interventions that lasted only a few class periods or a single instructional unit, which limited the capacity to observe sustained or transferable learning effects. Second, many studies did not include control groups or baseline comparisons, making it difficult to isolate the specific contribution of XR technologies to observed outcomes. Third, differences in pedagogical design and implementation quality likely contributed to inconsistent results. In studies where XR tools were integrated with clear learning goals, interactive scaffolding, or collaborative tasks, positive outcomes were more common. Interventions that used XR as a standalone or novelty tool tended to show weaker or negligible effects. Fourth, learner characteristics and contextual variables, such as prior experience with digital media, age, and subject matter familiarity, may have influenced how students responded to XR-based learning environments. Most studies relied on self-reported outcomes and post-intervention assessments, limiting the objectivity and depth of data on actual learning processes. These methodological and contextual limitations likely contributed to the lack of strength of current evidence base on XR's impact on learning.

This review was conducted with several methodological limitations that may have shaped the scope and composition of the included evidence. First, only English-language publications were considered, which may have excluded relevant studies conducted and reported in other languages, particularly given the global interest in XR. Second, the review excluded grey literature, technical manuals, and tool-specific validation studies, which may contain useful insights into the implementation and practical application of XR technologies. Meta-analyses and systematic reviews were also excluded to avoid redundancy and ensure a focus on primary studies.

Categorization of study outcomes using the Taxonomy 4.0 framework proved to be challenging. Multiple studies have found overlapping results without precise definitions or consistent operationalization. In some cases, outcome measures combined components from multiple domains (such as disciplinary and cognitive). The variability of study designs made the synthesis process even more challenging. The studies included both experimental and quasi-experimental interventions, as well as exploratory case studies, with significant differences in sample size, duration, instrumentation, and report quality. The diversity made direct comparisons difficult and limited the ability to identify strong patterns within the evidence base. Nevertheless, the Taxonomy 4.0 framework proved valuable in highlighting previously unexplored areas within the existing literature and identifying domains that warrant further research.

Conclusions

The current evidence provides limited insight into the long-term or general effects of XR in education. Many studies lacked methodological rigor, making it difficult to draw reliable conclusions from their findings. To advance the field, future research should incorporate reliable outcome measures, well-defined control groups, longitudinal designs, and diverse participant samples that reflect the complexity of real-world educational settings. This would help move the field beyond the proof-of-concept stage. While most existing research focuses on disciplinary and cognitive outcomes, many studies in the cognitive domain did not include objective assessments of cognitive functioning. To make more accurate and confident claims about the educational value of XR, we need higher-quality, better-defined evidence across a broader range of learning domains.

The literature reviewed rarely included teachers as co-designers in the development of XR technologies. Addressing this gap will require greater cross-sector collaboration among developers, researchers, and schools to ensure that XR tools are designed with classroom needs in mind. In addition, several studies reported issues related to access, highlighting the importance of considering equity and infrastructure in the implementation of XR in education.

Creating methodological standards is a critical policy priority, alongside ensuring adequate resources and equitable access. The studies reviewed varied widely in their design, measurement tools, and reporting practices, making it difficult to compare findings or build a cumulative evidence base. To improve the coherence and utility of future research, efforts should focus on developing a shared research infrastructure. This could include defining a core set of data elements, identifying appropriate functional outcome measures, and establishing minimum quality standards for XR intervention studies. Such standardization would enable more consistent evaluation across diverse contexts and support the development of a stronger, policy-relevant evidence base. The findings of this review underscore the need not only for pedagogical and infrastructural planning, but also for coordinated methodological guidance to shape the future of XR research and its effective application in education.

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