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Augmented reality and virtual reality in education: A systematic narrative review on benefits, challenges, and applications

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Abstract

Augmented reality (AR) and virtual reality (VR) have attracted increasing interest in the field of education, largely because of their potential to create immersive and stimulating learning environments. These technologies appear to offer alternative approaches to traditional instruction, enabling interaction between teachers and learners in virtual spaces. Several studies have suggested that AR and VR tools can increase student engagement across a range of subjects and provide meaningful support in classroom settings. This systematic narrative review investigates the benefits, challenges, and application domains of AR and VR in education by analyzing studies published over the past ten years. The literature was gathered from six major academic databases: Scopus, Web of Science, ScienceDirect, ERIC, IEEE Xplore, and the ACM Digital Library. Following the preferred reporting items for systematic reviews and meta-analyses 2020 guidelines, 53 relevant articles were identified and analyzed. The findings indicated mostly positive outcomes tied to the adoption of AR and VR in education, especially in improving learning. Simultaneously, several recurring challenges have been reported, posing barriers to widespread implementation. The review concludes by highlighting areas where further research is necessary to integrate these technologies into educational practices more effectively.

Keywords: augmented reality, virtual reality, narrative systematic review, education, immersive learning, technology enhanced education

INTRODUCTION

Augmented reality (AR) and virtual reality (VR) are not new technologies; their integration into the educational field has a long history. The first recorded implementation of a digital VR system appeared in 1966, notably, the flight simulator developed by the United States Air Force for training purposes. These early applications laid the foundation for the evolution of VR technology. Meanwhile, the term "virtual reality" was popularized by Jaron Lanier in the United States during the 1980s, while "augmented reality" was first coined in 1990 by researchers Thomas Caudell and David Mizell to describe head-mounted displays (HMDs) used by electricians assembling complicated wiring harnesses (Elmqaddem, 2019).

Since the 1990s, major companies have been using AR and VR technologies for visualization and training purposes. In recent years, advances in computing power and widespread availability of mobile devices have made it increasingly practical to incorporate AR and VR technologies into everyday educational settings. This technological progress has not only eased the integration of immersive tools into classrooms but also opened up new possibilities for interactive learning experiences (Diegmann et al., 2015).

The integration of AR and VR in education is grounded in several established learning theories. From a constructivist perspective, learners actively build their understanding of reality through the interaction of their prior knowledge and experiences. Learning becomes most effective when it is experiential and situated in authentic contexts, where the environment actively shapes learners' understanding (Kavanagh et al., 2017). AR and VR technologies naturally support these

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Contribution to the literature

- Provides a systematic narrative review of the benefits, challenges, and application domains of AR and VR in education over the past ten years.
- Synthesises evidence on how immersive technologies enhance learning outcomes, student engagement, and both cognitive and non-cognitive skills.
- Offers practical insights for educators, policymakers, researchers, developers, and institutions to guide effective integration of AR and VR into educational practices.

principles by providing immersive interactive environments that encourage exploration, interaction with content, experimentation, and active knowledge construction. In addition to constructivism, the use of AR and VR in education strongly aligns with the experiential learning principles. These technologies provide realistic and engaging experiences that enhance students' understanding by enabling them to visit historical sites, explore distant locations, and simulate scientific experiments. Through these immersive activities, learners can interact with the environment, manipulate objects, and collect data, thereby promoting active participation and experiential knowledge acquisition (Lytvynova & Soroko, 2023).

This review encompasses all levels of education, from primary to higher, acknowledging the potential of AR and VR technologies in enhancing learning across the education spectrum. By examining the integration of VR and AR across various levels, this review aims to offer insights broadly applicable to diverse educational contexts.

The central aim of this systematic narrative review was to provide a thorough and critical overview of how AR and VR have been adopted in education. Particular attention is paid to the pedagogical benefits they offer, the technical and institutional challenges encountered, and the domains in which these technologies have demonstrated the greatest potential for improvement. To guide this exploration, this review focuses on three central research questions (RQs).

RQ1. What benefits do AR and VR technologies offer to education?

RQ2. What challenges exist in applying VR and AR in an educational context, considering technological, pedagogical, and infrastructural aspects?

RQ3. What are the domains of VR and AR applications in education?

This study also reflects on future directions for the continued integration of AR and VR technologies into education, drawing on insights from the current body of research. In addition to this forward-looking perspective, it includes practical examples. It proposes several ideas that may support educators and researchers seeking to apply immersive tools to enrich learning and encourage pedagogical innovation.

METHODOLOGY

Information Sources

In this study, we conducted a systematic narrative review to examine the applications of VR and AR technologies in educational contexts. Systematic literature reviews are known for their rigorous, transparent, and replicable methods for identifying, assessing, and synthesizing existing research (Sarıtaş & Topraklıkoğlu, 2022). The review process followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA 2020) statement (Page et al., 2021), which helped ensure consistency, clarity, and high-quality reporting of the systematic reviews.

Selection of Databases

In selecting the sources for this review, six databases were chosen for their relevance to educational technology research and their strong presence in recognized academic indexing platforms. The goal was to capture a wide and representative sample of studies at the intersection of AR, VR, and education, while maintaining a high standard of academic reliability.

1. **Education Resources Information Center (ERIC):** a key resource for educational research focusing on peer-reviewed journal articles, reports, and other education-related materials.
2. **IEEE Xplore Digital Library:** Covers research on the intersection of technology and education, particularly in computer science and engineering.
3. **Scopus:** A multidisciplinary database with extensive coverage of peer-reviewed literature, including educational technologies.
4. Web of Science: Provides access to various academic disciplines with strong emphasis on high-impact research.
5. **Science Direct:** Offers access to a broad collection of scientific and technical research, particularly in engineering and technology.
6. **ACM Digital Library:** A specialized resource for computing and information technology, including applying these technologies in education.

Table 1. Systematic review sources: Search databases, strings, and number of results

Databases	Search items	Results
ERIC	("virtual reality" OR "augmented reality") AND education AND ("advantages" OR "benefits" OR "challenges" OR "barriers" OR "applications")	300
IEEE Xplore	(("Document Title": "virtual reality") OR ("Document Title": "augmented reality")) AND (("Document Title ": "education") OR ("Document Title": "teaching") OR ("Document Title": "learning"))	85
Scopus	(Title: ("augmented reality" OR "virtual reality" OR "VR") AND Title:(education))	35
Web of Science	(Title: ("augmented reality" OR "virtual reality" OR "VR") AND Title:(education))	772
Science Direct	(Title: ("augmented reality" OR "virtual reality" OR "VR") AND Title:(education))	172
ACM Digital Library	(Title: ("augmented reality" OR "virtual reality" OR "VR") AND Title:(education))	1,734

Note. Records identified from databases = 3,098

Search Strategy

The literature search was carried out on December 11, 2024, with a focus on identifying studies related to the integration of VR and AR in educational settings. To ensure relevance, a combination of targeted search strings was used, incorporating keywords such as "virtual reality," "augmented reality," and "education." Boolean operators were applied to refine the results and filter studies that specifically addressed the use of VR and AR technologies in learning environments. Particular attention was paid to studies published in 2024 because of their timeliness and relevance, contributing to a comprehensive and up-to-date analysis of the field.

Search terms and filters

The search terms were adapted to suit the structure and indexing practices of each database, ensuring both specificity and relevance in the retrieved studies. For instance, in IEEE Xplore, the search was narrowed to document titles in order to capture the most directly relevant publications on VR and AR in education. Similarly, the strategies used in the other databases were optimized to align with their respective indexing systems and subject coverage, helping to maximize the precision of the search results.

As shown in **Table 1**, an overview of the databases, search items, and the number of results retrieved during the literature search.

Additional sources

To further strengthen the comprehensiveness of the review, the reference lists of key articles were manually examined to identify additional relevant studies. This supplementary step aimed to capture any important research that may have been missed through the initial database search alone.

Selections process

The selection process for this review was guided by clearly defined inclusion and exclusion criteria along with a careful evaluation of the quality and relevance of each study. Full-text articles retrieved from the database searches were assessed against these criteria to ensure alignment with the review objectives. As outlined in **Table 2**, the selected studies were limited to those published between 2014 and 2024, written in English, and encompassed various study designs relevant to the use of AR and VR in education.

Data Collection Process

The data collection process followed the PRISMA 2020 framework (Page et al., 2021) and was organized into three main phases: identification, screening, and inclusion. These stages provide a structured approach to managing the literature and ensuring transparency and consistency throughout the review process.

1. **Identification:** A search across six selected databases yielded 3098 records. Using specified search strings and filters.
2. **Screening:** Bibliographic software was used to organize the references and remove duplicates. The initial set of 3,098 records was refined using database functionalities to exclude irrelevant publications based on the criteria.
3. **Inclusion:** After the initial screening, 1,837 studies were independently reviewed for relevance and quality. Following manual filtering based on the inclusion and exclusion criteria, 53 studies were selected for inclusion in the systematic review.

A detailed summary of the 53 reviewed studies, including the publication year, country, and methods, is provided in **Appendix A**.

The stages of study selection, illustrating the transition from initial identification to final inclusion, are visually represented as shown in the PRISMA 2020 flow chart (**Figure 1**).

Study Selection and Quality Assessment

The review team consisted of four authors, who acted as systematic reviewers throughout the process. Study selection was conducted independently by two reviewers following the PRISMA 2020 guidelines. Titles, abstracts, and full texts were screened based on predefined inclusion and exclusion criteria, as detailed in **Table 2**.

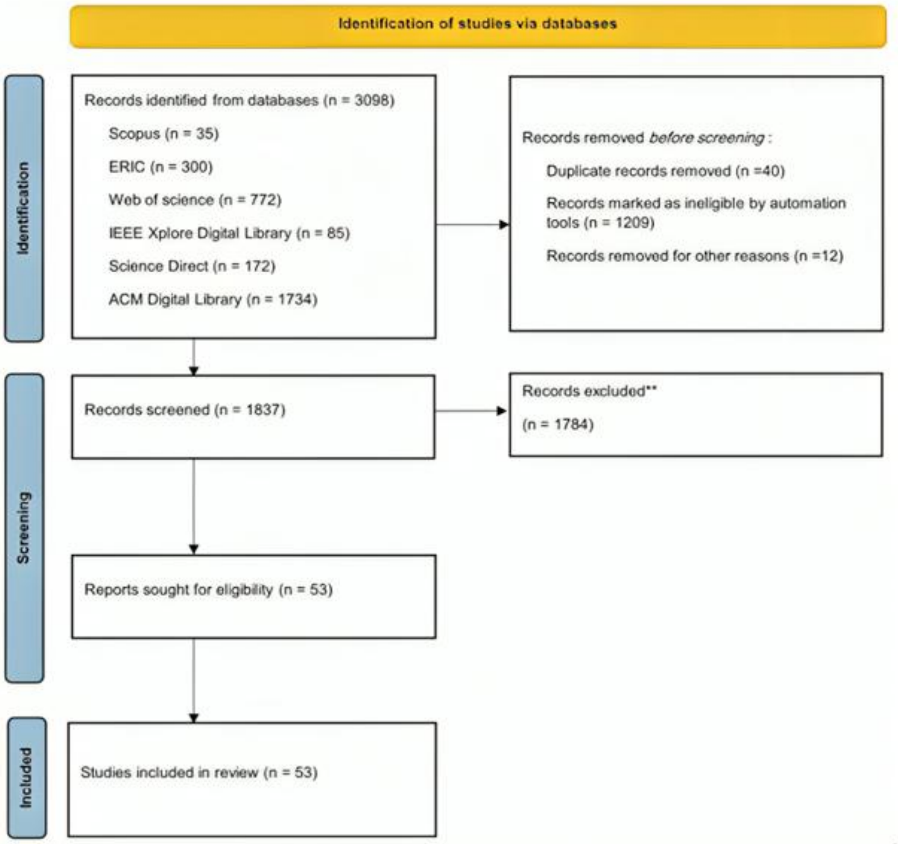

Figure 1. PRISMA 2020 flow chart (Source: Authors' own elaboration)

Table 2. Inclusion and exclusion criteria

Inclusion criterion (IC)	Exclusion criterion (EC)
IC1: Studies focusing on educational technologies within the education domain, including VR and AR	EC1: Studies that are not explicitly focused on VR and AR within the education domain
IC2: Document types: Book chapters, case studies, journal articles, proceeding papers, or reviews	EC2: Document types: Book reviews, editorials, notes, whole books
IC3: Studies published within the last ten years (2014-2024)	EC3: Studies published outside the timeframe of the last ten years (2014-2024)
IC4: Full-text studies	EC4: Non-full-text works
IC5: Studies published in English	EC5: Studies not published in English

Reviewer agreement was ensured through consensus meetings whenever discrepancies occurred, and a third reviewer from the team served as an arbitrator when needed. Inter-rater agreement was calculated using Cohen's kappa coefficient (κ = 0.82), which indicated strong consistency among the reviewers. The methodological quality of the included studies was evaluated using the mixed methods appraisal tool. Two reviewers independently performed the assessment, and any disagreements were resolved through discussion until a consensus was achieved with the involvement of a third reviewer.

RESULTS

In this section, we present the results of the specific subsections, effectively addressing the RQs mentioned in the introduction section.

Evolution of AR/VR in Education (2014-2024)

Over the past decade, AR and VR technologies have undergone significant evolution, shaping their adoption and impact on educational settings. This section presents a timeline of key developments from 2014 to 2024, highlighting the technological advancements, pedagogical shifts, and emerging trends. As outlined in **Figure 2**, the key milestones in AR/VR adoption in education from 2014 to 2024 highlight significant technological and pedagogical advancements.

2014. Google Cardboard introduces affordable VR for education

The introduction of Google Cardboard revolutionized VR accessibility with low-cost, mobile-friendly devices, sparking initial educational use for immersive, passive learning experiences (S M et al., 2016).

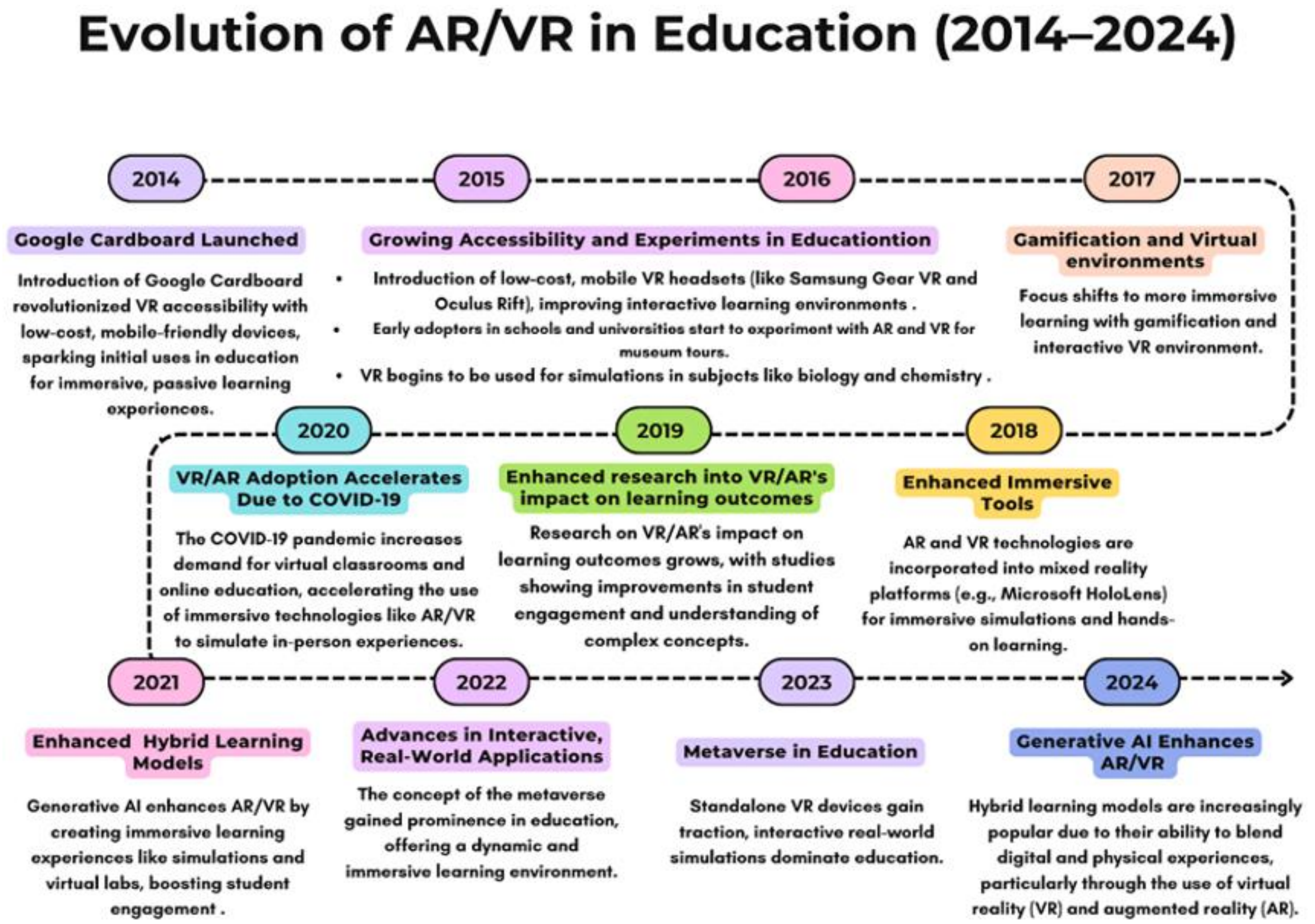

Figure 2. Evolution of VR and AR in education (2014-2024): Key technological advancements, pedagogical shifts, and emerging trends (Source: Authors' own elaboration)

2015-2016. Accessibility grows with mobile VR adoption and early experimental educational uses

The introduction of low-cost VR devices, such as the Oculus Rift DK2, significantly expanded access to immersive learning environments by reducing financial barriers and enabling broader experimentation in educational contexts (McNamara et al., 2016). Early adopters at schools and universities experimented with AR and VR for museum tours (Yáñez et al., 2015). VR has been used in biological and chemical simulations (Almazaydeh et al., 2016).

2017. Increased focus on gamification and interactive VR learning simulations

The focus shifted towards more immersive learning experiences and integrating gamification and interactive VR environments to enhance student engagement and participation (Kavanagh et al., 2017).

2018:. Enhanced immersive tools

Immersive simulations and hands-on learning experiences that enable learning by doing are facilitated by mixed-reality platforms, such as Microsoft HoloLens, which integrate AR and VR technologies (Leonard & Fitzgerald, 2018).

2019. Enhanced research into VR/AR's impact on learning outcomes

Studies showing the impact of VR/AR on learning have been increasing, with numerous studies across various contexts showing substantial gains in both engagement and understanding of complex concepts when students work with AR and VR.

2020. Adoption accelerates during the COVID-19 pandemic with the rise of virtual classrooms

The COVID-19 pandemic has accelerated the adoption of immersive technologies, such as AR and VR, to simulate in-person experiences, driven by the increased demand for virtual classrooms and online education (Pears et al., 2020).

2021. Hybrid learning models gain popularity by blending digital and physical experiences

Hybrid learning benefits from AR and VR, which creates immersive and interactive settings. These cater to various learning styles and engage all types of learners.

These technologies support not only in-person learning, but also remote education, creating a richer overall experience (Sala, 2020).

2022. Standalone VR devices gain traction, and interactive real-world simulations dominate education

Standalone VR devices have gained traction by 2022, and simulations of real-world interactions have become mainstream in education. Virtual laboratories allow students to conduct experiments in safe, controlled environments, enhancing their understanding of complex scientific concepts (Rahman et al., 2022). VR has also become more accessible to everyday consumers, with various headsets available on the market, including HTC Vive, Samsung VR, Oculus, and Google Cardboard (Hamad & Jia, 2022).

2023. The Metaverse for education begins with virtual campuses and social learning tools

By 2023, the concept of the metaverse had gained prominence in education, offering a dynamic and immersive learning environment. Metaverse enables a more profound exploration of scientific concepts, historical events, and cultural artefacts, fostering active communication, collaboration, and critical thinking (CT). This shift marks a significant evolution from standalone AR and VR applications to fully integrated virtual learning ecosystems (Pradana & Elisa, 2023).

2024. Generative AI enhances AR and VR

The integration of generative AI in 2024 brought AR and VR education to new heights. It enabled the creation of interactive and immersive learning materials, such as simulations and virtual labs, that held students' attention and encouraged them to engage in active participation. The AR and VR experiences included game-based learning (GBL) environments that enabled students to learn concepts more engagingly and playfully, resulting in a net increase in the richness of their educational experiences (Dhagare, 2024).

RQ1. What Benefits Do VR and AR Offer for Education?

Increased motivation and interest

Kavanagh et al. (2017) defined motivation as the desire or incentive that drives students to actively engage in learning activities. Yildirim (2020) expresses this idea effectively when he states that students are more willingly, happily, and excitedly learning lessons supported by AR applications, and are more actively engaging in classes. In a similar study, Al-Ansi et al. (2023) illustrate that students utilizing AR and VR technologies have been found to have higher levels of motivation and engagement, as well as better academic performance. Furthermore, they highlighted the potential of AR and VR technologies to create a more immersive and interactive learning experience. Through these technologies, students can be exposed to engaging visuals and audio cues, effectively enhancing their interest in the subject matter. Yilmaz and Coskun Simsek (2023) emphasized the positive effects of AR and VR in education, noting that these tools increase students' motivation and interest.

As Diegmann et al. (2015) suggested, employing AR applications in specific ways is more likely to lead to certain benefits, such as increased motivation. Moreover, Arici et al. (2019) noted that in recent years, AR technology has gained prominence in fields such as mathematics and science, enhancing students' engagement and immersing them in a personalized learning environment. Combining virtual and real objects, providing real-time interaction, and presenting 3D objects are the key features of AR technology, resulting in a unique learning experience that creates a sense of reality.

Furthermore, Lyu et al. (2023) emphasized the potential of AR to blend physical and virtual worlds, bringing familiar backgrounds or personalized objects into games. This integration enables a safer and more connected experience, contributing to the overall positive impact of AR on motivation and engagement in educational settings.

Research conducted by Anuar et al. (2021) has demonstrated that student motivation can be enhanced by utilizing AR learning materials. Their study demonstrated that when students interacted with AR learning materials, their motivation levels increased from a moderate level, typical of most students, to a high level more characteristic of students who are the most successful in school.

Additionally, researchers noted that students anticipated an increase in motivation resulting from the integration of VR in educational settings, particularly with its use for immersive experiences and virtual tours (Feridun & Bayraktar, 2024).

The results provide evidence that engagement and motivation are enhanced through the use of tools such as AR and VR. This is important, because engagement and motivation are directly tied to better learning outcomes.

Improve learning outcomes

The applications of AR and VR have been shown to significantly boost academic success. Yildirim (2020) highlighted that AR applications are notably impactful, as they enhance students' learning outcomes by improving their comprehension of the subject matter. Pelin Yildiz and Yildiz (2022) expresses an affirmative consensus on the educational value of AR applications, specifically naming Arloopa as an application that engages students and enhances their learning outcomes effectively. Additionally, Srimadhaven et al. (2020)

highlighted that VR can enrich the learning experience through engaging and enjoyable activities, motivating learners and leading to better academic performance. Furthermore, AR and VR technologies improve learning outcomes by developing essential digital-age skills, including digital literacy, creative thinking, communication, collaboration, and problem-solving. These skills are critical for achieving 21st century competencies (Papanastasiou et al., 2019). Moreover, research has shown that the application of AR in science classes leads to measurable increases in student achievement and more favorable student attitudes, indicating that these technologies are effective in enhancing educational outcomes (Çetin & Türkan, 2022).

Addressing inaccessible environments

According to Al-Ansi et al. (2023), the transformative solution provided by AR and VR technologies is that they enable an even more accessible learning experience for not only the average student found in any classroom, but also for students with special needs. These technologies provide individuals with the opportunity to explore virtual environments at a pace and on terms that suit their unique situation. In essence, these virtual environments can be more easily navigated by individuals with physical impairments or cognitive disabilities, because they are given more control in a situation where the typical classroom might present more hurdles. Moreover, VR technology enables users to replace their current reality with virtual environments, pushing past the boundaries of the physical world and allowing them to access educational materials and environments that would be difficult or impossible to reach under normal circumstances (Lege & Bonner, 2020).

Distance learning

VR possesses the potential to broaden learning horizons by reaching beyond traditional in-person education and new locations and demographics. Its capacity to unite individuals over vast distances and create immersive settings for interaction could address the limitations of the existing online learning and distance education methods (Lege & Bonner, 2020). Both VR and AR facilitate distance learning by enabling trans-local teaching, which allows students to engage with virtual environments that enhance their educational experiences beyond physical boundaries (Ntaba & Jantjies, 2019).

To address the demand for distance learning during the COVID-19 pandemic, the Saudi Ministry of Education launched the iEN educational portal. This platform combines AR features with e-textbooks and a host of other multimedia resources. This initiative has significantly enhanced accessibility and interactivity in remote learning environments (AlNajdi, 2022).

Enhancing accessibility and inclusion for students with disabilities

The integration of VR and AR technologies significantly enhances the educational and social experiences of students with disabilities. These immersive tools facilitate learning, foster social interaction, and promote emotional development. According to Mohamed et al. (2024) VR and AR can be particularly beneficial for children with autism spectrum disorders by encouraging communication and cooperation within the classroom. By offering interactive educational structures that enhance teamwork and problem-solving skills, these technologies help children engage with society better. Additionally, VR and AR create simulations that allow children to interact in ways that are not possible in traditional classroom settings, improve social skills, reduce anxiety, and provide a more inclusive learning experience (Mohamed et al., 2024). Moreover, providing educators with training to effectively integrate AR and VR technologies into their teaching practices is crucial. This includes equipping them with strategies for creating an inclusive classroom environment, ensuring that all students, including those with special needs, can benefit from these technologies.

A significant case study demonstrated the use of an AR system to teach mathematical concepts to children with autism. The study demonstrated that children using AR significantly improved their mathematical skills compared to those taught using traditional methods. AR technology not only increased engagement and motivation but also proved particularly effective for children who struggled with conventional instruction (Asatryan et al., 2023). This underscores the potential of AR in creating more inclusive and effective learning environments for students with special needs.

Enhancing non-cognitive skills and collaboration

The significance of CT skills among students lies in their ability to actively assess, evaluate, and respond thoughtfully. Research indicates that AR and VR significantly enhance non-cognitive skills such as CT and student collaboration. For instance, a quantitative study by Hanggara et al. (2024) demonstrated that a GBL model using AR significantly enhanced CT skills among eighth-grade students. Seventy-seven students participated in the study, comprising 40 in the experimental group, who used AR-based games, and 37 in the control group, who received traditional teaching methods. This research employed a valid and reliable test to measure students' CT skills, ensuring the credibility of the results. The findings revealed that students in the experimental group exhibited more substantial improvements in their CT skills compared to those in the control group, underscoring the effectiveness of AR in promoting learning. These results suggest that integrating AR technology into education

Figure 3. Thematic word cloud of AR and VR benefits in educational contexts (Source: Authors' own elaboration, using https://wordart.com/)

fosters more engaging and interactive learning environments, thus supporting the development of CT skills.

According to Papanastasiou et al. (2019), virtual environments can potentially create shared experiences for students and instructors, enabling collaborative work and practical demonstrations of instruction. Students can create or join existing groups by participating in emerging social networks within these environments, further enhancing collaboration and social interactions in educational settings. Ultimately, AR and VR support the development of not only cognitive skills but also essential non-cognitive skills, contributing to a more holistic educational experience.

As presented in **Figure 3**, the most frequently reported benefits of AR and VR in education include enhanced engagement, motivation, learning outcomes, and the development of non-cognitive skills, such as collaboration and CT.

Examples of AR and VR applications in education

Based on this research by Medvedieva and Yamkovenko (2024), numerous applications have been developed to integrate them into the educational process. Below, we explore some of the most common and impactful applications. These applications demonstrate the diverse benefits of AR and VR technologies in education, categorized by their impact on motivation and engagement, accessibility, learning outcomes, enhancement of non-cognitive skills, collaboration, and distance learning.

Motivation and engagement

1. **GeoGebra AR:** Enables users to create and view 3D mathematical objects in the real world, providing enhanced visual support for learning complex concepts in geometry and functions. This interactive tool dynamically engages students to understand mathematical concepts.
2. **AR Solar System:** Offers users the ability to view and interact with a 3D model of the solar system and its planets. This application provides a realistic and immersive exploration of outer space, capturing students' interest.
3. **Google Arts & Culture:** Offers interactive journeys and virtual tours of historical and cultural sites, utilizing AR and VR technologies. It enhances learning by offering immersive experiences and virtual exploration.

Accessibility

1. **Anatomy Learning–3D Anatomy:** Enables users to study human anatomy through detailed 3D models and AR elements. Users can interact with and explore body systems, making it easier to understand anatomy through interactive visualizations.
2. **ClassVR:** Offers VR experiences tailored for students with special needs, providing more accessible and engaging learning environments. This application supports various learning needs through customized VR content.
3. **Osmos VR:** Offers virtual science lessons tailored to students with mobility challenges, enabling them to access and engage with science education in a virtual environment.

Learning outcomes

1. **AR Flashcards:** AR enhances vocabulary learning for young children. The interactive AR flashcards enhance engagement and language acquisition, leading to improved learning outcomes.
2. **Labster:** Provides virtual science laboratories for conducting experiments and understanding complex concepts. This tool enables students to engage in hands-on virtual lab activities, thereby enhancing their understanding of scientific principles.
3. **CleverBooks Geometry:** Teaches geometric shapes and concepts using AR, including interactive exercises and tests. This application helps users learn and test their knowledge of geometry interactively.

Distance learning

1. **AltspaceVR:** Facilitates virtual classrooms where students can meet and collaborate in an immersive environment. It supports virtual interaction and collaboration by bridging geographical distances.
2. **Google Tilt Brush:** A VR application for drawing and creating 3D objects, allowing users to interact with their creations in three-dimensional space. This tool fosters creative expression in a virtual setting.

Table 3. Summary of AR and VR applications categorized by educational benefits and uses

Category	Applications
Motivation and engagement	GeoGebra AR, AR Solar System, Google Arts & Culture
Accessibility	Anatomy Learning – 3D Anatomy, ClassVR, Osmos VR
Learning outcomes	AR Flashcards, Labster, CleverBooks Geometry
Distance learning	AltspaceVR, Google Tilt Brush, VRMath2
Enhancing non-cognitive skills and collaboration	Google Arts & Culture, ClassVR, Labster, CleverBooks Geometry, AltspaceVR, Google Tilt Brush

3. **VRMath2:** A VR application designed for learning mathematical concepts through comprehensive video tutorials. It provides an immersive learning experience in VR, aiding in math education.

Enhancing non-cognitive skills and collaboration

1. **Google Arts & Culture:** Encourages exploration, CT, and cultural awareness through immersive virtual tours.
2. **ClassVR:** Supports various learning needs and fosters collaboration among students with special needs through customized VR experiences.
3. **Labster:** Enhances problem-solving and CT by providing virtual science laboratories for experimentation.
4. **CleverBooks Geometry:** Promotes CT and spatial reasoning through interactive geometry exercises.
5. **AltspaceVR:** Facilitates virtual collaboration and teamwork in an immersive environment.
6. **Google Tilt Brush:** Encourages creativity and artistic expression through 3D drawings and interaction in a virtual space.

As illustrated in **Table 3**, a summary of the AR and VR applications analyzed in this study is presented, categorized by their primary educational benefits.

Defining and measuring increased student academic performance

To effectively evaluate the impact of AR and VR technologies on students' academic performance, it is crucial to define and measure outcomes with precision. This subsection outlines a comprehensive approach to evaluating the impact of immersive technologies on student learning and performance.

Definition of increased academic performance

Increased academic performance is characterized by measurable improvements in students' understanding, skills, and overall achievement in educational settings, resulting from the integration of AR and VR technologies. This includes enhanced comprehension of subject matter, higher test scores, improved engagement, and positive feedback from educators and students (Papanastasiou et al., 2019; Pelin Yildiz & Yildiz, 2022; Srimadhaven et al., 2020; Yildirim, 2020).

Measurement methods

Student academic performance is assessed through both quantitative and qualitative measures.

1. **Quantitative measures**
   a. **Pre- and post-intervention assessments:** Academic performance was assessed through standardized tests or quizzes administered before and after AR and VR tools were implemented. For example, a study on geometry instruction might use pre-tests to gauge initial understanding and post-tests to measure knowledge gained after using AR applications like GeoGebra AR.
   b. **Test score analysis:** The improvement in test scores provides a quantitative measure of academic performance. Statistical analysis of the test results helped to determine the significance of the observed changes.
2. **Qualitative measures**
   a. **Surveys and interviews:** Structured surveys and interviews were administered to gather feedback from the students and educators. These tools may include questions about the usability of AR and VR tools, their impact on understanding the course material, and the perceived benefits or challenges of integrating these technologies into the learning environment.
   b. **Educator feedback:** In addition to surveys, structured interviews, or open-ended teacher feedback provided qualitative data on students' progress. Educators can offer detailed observations on how AR and VR tools affect students' conceptual understanding, problem-solving abilities, and motivation.

Case study examples

In addition to the general benefits discussed, specific case studies have illustrated the positive impact of AR and VR in education. For example, integrating AR and VR in mathematics education has shown promising results in enhancing student engagement and understanding of complex concepts. A case study involving students from grades three to eight demonstrated that AR and VR tools, particularly through platforms like Cospaces Edu, significantly boosted motivation and facilitated meaningful learning

Figure 4. Integration of content into the real environment with the Arloopa AR application (Pelin Yildiz & Yildiz, 2022)

experiences by incorporating storytelling and game-like environments (Bertrand et al., 2024). This project has resulted in substantial improvements in student engagement and understanding, underscoring the effectiveness of AR and VR in creating interactive and immersive learning experiences.

Another example comes from a case study involving the Arloopa application, in which 27 students participated in an AR course at a government university in Turkey. The course integrated Arloopa to enhance learning experiences by embedding digital content into real-world environments. An interview form was applied to gather qualitative data, consisting of demographic information and four open-ended questions. The results indicated that students found using AR applications beneficial, particularly in making lessons more enjoyable, fostering creativity, and aiding in the comprehension of complex subjects. Despite these positive effects, some students noted that the cost of certain AR applications could be a limitation. This case study underscores the potential of AR tools like Arloopa to significantly enhance student engagement and learning outcomes, particularly by making the learning process more interactive and enjoyable (Pelin Yildiz & Yildiz, 2022). As depicted in **Figure 4**, the content is seamlessly integrated into the physical environment through the Arloopa AR application.

RQ2. What Challenges Exist in Applying VR and AR in an Educational Context, Considering Technological, Pedagogical, and Infrastructural Aspects?

Lack of VR and AR specific pedagogy

While there is a possibility of integrating VR into established educational paradigms with some success, researchers concur that unlocking its learning potential requires a solid pedagogy associated with VR (Lege & Bonner, 2020). Moreover, Elmqaddem (2019) mentioned, "*it will be necessary to know how to build and deploy educational programs well adapted to this technology*".

Additionally, Lege and Bonner (2020) highlighted that the primary challenge in integrating VR into education lies in figuring out the optimal way to utilize this technology to significantly improve students' learning experiences without simply replicating or substituting the traditional physical classroom. Acknowledging this, recent developments have focused on formulating a pedagogy specifically designed for VR. For instance, the Actioned Pedagogy for Immersive Learning, developed by Southgate in 2020, guides educators delving into VR to consider crucial aspects related to the teacher, students, and technology itself (Lege & Bonner, 2020).

In discussions about pedagogies related to VR in education, there is a predominant focus on constructivist-based approaches. Though pedagogical beliefs are not explicitly tied to constructivism, they often align closely. For instance, there is a notable emphasis on the value of play as an intellectual activity and the VR systems' capability to facilitate students' exploration within the educational environment. This underscores the prevailing association and influence of constructivist principles in pedagogical discussions, even indirectly (Kavanagh et al., 2017).

Furthermore, Sarkar and Pillai (2021) highlighted the challenges in designing AR Learning Experiences (ARLEs) and AR authoring tools. They noted the growing research on novel ARLEs but expressed a lack of insights into the design process, especially concerning the synergy between content, pedagogy, technology, and design. The iterative process involved in creating this synergy has rarely been discussed, and a notable gap exists in understanding the appropriate design strategies and decisions required to develop ARLEs effectively within the classroom context.

Cost

The major challenges faced by AR and VR in education revolve around costs. The required hardware and software for these technologies often come with high expenses, exceeding the budgets of many schools. Additionally, the need for regular software updates to create immersive experiences can result in additional costs, further compounding the affordability challenge for educational institutions (Al-Ansi et al., 2023). Moreover, a study by Familoni and Onyebuchi (2024) highlighted that high costs and the need for suitable technical infrastructure are significant barriers to the widespread adoption of VR and AR technologies in education. The initial investment for VR headsets and AR devices can be prohibitive, especially for educational institutions with limited budgets. Furthermore, due to a lack of funding in the education sector, not all educational institutions can afford the expensive equipment needed to implement immersive technologies in the educational process. This financial barrier limits the ability of many schools to provide access to AR and VR resources, thereby hindering the integration of these innovative tools into their curricula (Medvedieva & Yamkovenko, 2024). Despite its apparent promise, the high cost and immobility have been the challenges in scaling up this approach (Lyu et al., 2023).

Software usability

As highlighted by Kavanagh et al. (2017), the diversity of usability issues in AR and VR software is influenced by various factors related to the software's design and user interaction. These issues include:

1. **Complex interface design:** AR and VR applications often feature complex interfaces that can overwhelm users, particularly those who are not technologically savvy. The challenge lies in navigating multiple layers of menus, understanding the function of various buttons, and effectively interacting with virtual elements, which can hinder the overall user experience.
2. **Interaction quality:** The quality of the interaction with AR and VR software is critical. Users may experience difficulties in achieving precise interactions due to poor responsiveness or lag in the system. For instance, virtual objects might not respond accurately to user inputs, leading to frustration and reduced effectiveness of the learning experience.
3. **Readability and visual clarity:** Some AR and VR applications struggle with readability issues, particularly when displaying text or detailed content within a virtual environment. The resolution and clarity of visuals can be insufficient, making it difficult for users to read instructions or interact with on-screen elements effectively.

Additionally, Kavanagh et al. (2017) outlined that unfamiliarity with AR and VR technologies can exacerbate these usability challenges. Users new to these technologies may struggle to adapt to the novel ways of interacting with the software, which could impact their learning outcomes.

Hardware usability

Kavanagh et al. (2017) also addressed the usability challenges associated with the hardware required for VR implementations:

1. **Specialized hardware requirements:** VR often necessitates the use of unique hardware, such as HMDs and motion controllers, which may not be familiar to all users. The need for these specialized devices can be a barrier, as users may need time to learn how to operate them effectively.
2. **Physical demands:** Using VR hardware can place significant physical demands on the user. Prolonged use of HMDs, for example, can lead to discomfort, eye strain, or fatigue, which may limit the duration of effective learning sessions (Elmqaddem, 2019; Pelin Yildiz & Yildiz, 2022). Additionally, some VR setups require the user to stand or move around, which can be physically taxing, particularly for extended periods.
3. **Inaccurate interaction devices:** The accuracy of the input devices in VR environments, such as motion controllers or hand-tracking sensors, can vary. Less accurate devices can lead to imprecise actions within the virtual space, making tasks more challenging to complete and potentially detracting from the learning experience.

Accessibility

According to Al-Ansi et al. (2023), an additional challenge is accessibility. Not every student possesses the required hardware and software, necessitating that educational institutions devise means to ensure universal access for all learners.

Complexity

According to the analysis by Al-Ansi et al. (2023), one more challenge of AR and VR lies in their complexity. Given that these technologies are relatively new, their use can prove challenging for teachers and students who lack prior knowledge or experience with such systems. Furthermore, effective organization of interaction using VR and AR in education requires careful consideration of educational space and pedagogical methodologies, as participants' interactions often need improvement and specific guidance (Lytvynova & Soroko, 2023). This complexity can pose a challenge to educators as they integrate immersive technologies into their teaching practices. Ensuring that teachers and students can effectively utilize these tools necessitates adequate training, clear instructional design, and ongoing support to maximize the potential of AR and VR in enhancing the learning experience.

Health risks of VR and AR use

1. **Comfort and accessibility:** In VR and AR, the design and usability of headsets play a critical role in user comfort. Research has emphasized the need for engineers to focus on creating VR and AR headsets that prioritize ergonomic design and accessibility (Elmqaddem, 2019). Headsets should be designed to fit a wide range of users comfortably, minimizing physical strain and maximizing ease of use. This includes considerations of headset weight, padding, and adjustability.

Figure 5. Thematic word cloud of AR and VR challenges in educational contexts (Source: Authors' own elaboration, using https://wordart.com/)

2. **Physical discomfort:** Extended use of VR and AR headsets can lead to physical discomfort, which is a notable concern in educational settings. Studies have reported symptoms such as eye strain, headaches, and neck pain (Pelin Yildiz & Yildiz, 2022). Prolonged exposure to VR environments can exacerbate these issues, particularly among younger users whose bodies are still developing. To mitigate these risks, it is advisable to limit the duration of VR sessions and incorporate regular breaks to reduce strain. In addition, proper adjustments of headsets to ensure a comfortable fit, along with guidelines for safe usage, should be established to prevent users from experiencing undue physical discomfort.

Others consideration

In a study conducted by Lege and Bonner (2020), the significance of considering gender dynamics in integrating VR within classroom activities, particularly in secondary education, was highlighted. The research shows that compared to boys, girls have limited exposure to VR using HMDs. Moreover, wearing HMDs led to discomfort and feelings of embarrassment among some girls. This underscores the urgency of addressing gender-related concerns, including notions of femininity, masculinity, and the concept of the 'male gaze' in VR environments. These issues become prominent as users cannot perceive others' gazes or their appearance to others while immersed in the virtual classroom setting.

As illustrated in **Figure 5**, the most frequently reported challenges of AR and VR in education include technical issues, high equipment and maintenance costs, health risks, and a lack of AR/VR-specific pedagogy and teacher training.

Ethical considerations in the use of AR and VR technologies in education

As users engage with virtual environments and digitally augmented realities, a multitude of ethical issues have emerged (Zallio et al., 2024). These include:

1. **Protecting user rights and privacy:** One of the critical challenges in integrating AR and VR technologies into education is ensuring the privacy and security of student data. These technologies often collect detailed information about students' interactions, learning patterns, and sometimes even biometric data. To address these concerns, it is essential to ensure compliance with data protection regulations, such as the general data protection regulation (European Union, 2016), and to obtain informed consent from students and their guardians. This includes anonymizing data, using encryption, and allowing students to opt out of data collection.
2. **Health risks and governance frameworks:** Beyond individual discomfort, broader health considerations warrant further attention. Governance frameworks for immersive technologies should address these risks by setting clear guidelines and best practices for the safe use of VR and AR (Zallio et al., 2024). These include recommendations for screen time, ergonomic adjustments, and regular health monitoring to ensure user safety. By integrating these practices into the development and deployment of immersive technologies, educational institutions can help prevent adverse health effects and promote a safer learning environments.

RQ3. What Are the Application Domains of VR and AR in Education?

STEM education

The applications of VR and AR in science, technology, engineering, and mathematics (STEM) education have evolved significantly. Sırakaya and Alsancak Sırakaya (2022) highlighted that the integration of AR within STEM education has a significant positive impact on student engagement, motivation, and overall learning outcomes. AR has proven to be a valuable tool for enhancing students' comprehension of complex concepts and for refining their problem-solving skills. Additionally, AR fosters collaborative learning and provides personalized, adaptive educational experiences, underscoring its diverse contributions within STEM education.

Ibáñez and Delgado-Kloos (2018) pointed out that most AR applications for STEM learning focus on exploration or simulation activities, utilizing digital knowledge discovery mechanisms for information consumption. As highlighted by Boyles (2017), the early uses of VR in science education involved visualizing chemical reactions and learning about molecules by assembling them in virtual environments. More recent applications include marker-based AR for visualizing biological processes, such as respiration and human meiosis, and astronomy applications using an HMD to explore the solar system and provide students with a sense of scale. Boyles (2017) further noted that VR and AR technologies have made it possible to visualize abstract concepts that are challenging to relate to real-world experiences, such as teaching electromagnetism and the interaction between different circuit elements through marker-based AR applications.

The findings from these studies underscore the considerable transformative potential of AR and VR technologies in revolutionizing STEM education, effectively bridging theoretical knowledge with practical applications to create more meaningful learning experiences.

Geography education

According to Bos et al. (2022), both VR and AR technologies and content serve as valuable resources for geography education, offering immersive experiences and exploration opportunities.

A successful case study involved using an AR sandbox in a master's program for Flood Risk Assessment, Modelling, and Engineering. This case study utilized AR technology to enhance learning by allowing students to design and manipulate flow structures in real-time within a physical sandbox that projected a virtual topographic map. This interactive approach significantly improved students' understanding of hydrological concepts and flood scheme design. It provides insights into VR and AR applications in real-world scenarios, such as search and rescue operations. Feedback from students highlighted the AR sandbox's effectiveness in understanding complex hydraulic processes and its positive impact on their career prospects (Bos et al., 2022).

Another successful case study explored the use of VR for human geography fieldwork preparation. In this study, VR was employed to prepare students for a field trip to Snowdonia National Park in Wales. Using static 360-degree images and video footage captured from the field sites, students engaged with VR content to observe and analyze landscapes, identify human influences, and practice methodological techniques. This VR preparation allowed students to familiarize themselves with the fieldwork environment, conduct risk assessments, and develop observational skills before the actual field trip (Bos et al., 2022).

Ultimately, combining VR and AR technologies is pivotal for augmenting geography education by improving fieldwork, analytical abilities, and nurturing crucial employability skills.

History education

Drawing insights from the study by Yildirim et al. (2018), the integration of VR technologies in history education has demonstrated a profound impact on student engagement and learning outcomes. VR environments have been particularly effective in illuminating historically significant events, such as wars, treaties, and negotiations, by offering immersive and experiential learning opportunities. This study emphasizes that VR facilitates historical excursions, significantly enhancing the effectiveness of history education.

VR glasses, as highlighted by Yildirim et al. (2018), have become essential tools in this transformation. They enable students to explore historical sites visually, interact with past structures, and immerse themselves in reconstructed environments, thereby reducing their reliance on traditional textbooks and redefining the historical learning experience. Furthermore, Yildirim et al. (2018) note that VR creates a palpable sense of reality and presence, significantly increasing student engagement and interest in historical courses. This technology also enables students to visit inaccessible locations, creating tangible and immersive learning environments. Students appreciate the educational content accessible through VR glasses, particularly those facing mobility challenges or financial constraints.

These insights underscore the substantive utility of VR technologies in historical education and highlight their promise in transforming the educational experiences for diverse learners.

Language learning

Huang et al. (2021) highlighted the extensive use of AR and VR tools in language learning, particularly for vocabulary acquisition and overall skill development. These technologies support a range of language skills, including reading, listening, grammar, speaking, and writing. The immersive nature of AR and VR creates virtual environments enriched with 3D images, videos, and interactive games, thereby enhancing the learning experience. Despite its discontinuation, former AR tools such as Aurasma played a significant role in language learning by offering interactive features that aided vocabulary acquisition and visualized word meaning. Recognizing its historical impact provides valuable insights into the evolution of AR technologies in education, reflecting on their contributions, strengths, and limitations before their discontinuation.

A successful case study involved an experimental study examining the effectiveness of AR applications in teaching the English alphabet to kindergarten children in Kuwait. The study compared an experimental group using AR apps with a control group taught using traditional methods. A total of 42 preschoolers participated, with 21 in each group. The findings showed statistically significant advantages for the AR group in terms of interaction with the lesson and performance on the English alphabet test. The AR group demonstrated better engagement and higher test scores, highlighting the strong correlation between AR-based learning and improved educational outcomes. This study suggests further exploration of AR technology in education and offers recommendations for its implementation (Safar et al., 2017).

Geometry mathematics

VR and AR have shown potential in mathematics education. This research by Yilmaz and Coskun Simsek (2023) suggests that these technologies can enhance the quality of learning and improve teaching methodologies. They are particularly effective for teaching subjects or modules that require visual material, such as geometry and space geometry. Additionally, the research indicates that these technologies can be utilized to teach solid bodies, showcasing shapes in three dimensions. Instead of mandating students to memorize formulas, virtual representations allow them to visualize the derivation of these formulas.

According to Schutera et al. (2021), the abstract mathematical learning content, particularly in subjects such as vector geometry, can be challenging for many students. Researchers have proposed the use of AR as a solution to overcome these challenges. The AR application cleARmaths, presented in this research, aims to facilitate the understanding of vector geometry and parametric equations. It allows students to visualize geometric objects overlaid in a real environment, actively engaging them in the learning process. The application encourages interactive learning by allowing students to manipulate figures and parameters at their own pace.

Physics education

AR and VR technologies have proven to be particularly effective in enhancing physics education by transforming abstract concepts into more tangible and engaging learning experiences. Research has shown that AR and VR tools facilitate experiential learning through virtual experiments and simulations, that are often difficult to conduct in traditional classroom settings. By promoting active learning, these technologies improve students' understanding, retention, and curiosity, motivating them to apply physics principles in real-world scenarios. As these tools become more accessible, they have the potential to revolutionize physics education, making it more interactive and effective (Prayogi & Verawati, 2024).

A study by Rahmat et al. (2023) demonstrated that students who utilized mobile AR in their physics lessons achieved higher learning outcomes than those who relied on traditional textbooks. Student feedback indicated that AR technology made the learning environment more engaging and enjoyable, facilitating the understanding of abstract concepts through 3D visual simulations and making complex ideas more concrete. As a result, AR has contributed to better comprehension and improved academic achievement in physics.

Additionally, research on physics learning media based on AR has been positively received by students and teachers, demonstrating its effectiveness in simplifying complex topics, such as magnetic fields. The study confirms the feasibility of using AR as a tool in physics education, making abstract concepts more accessible and engaging for students, and further highlighting AR's potential to enhance learning experiences in physics (Isma et al., 2024).

Computer science education

Research has demonstrated the benefits of integrating VR and AR technologies into computer science education. The study by Pirker et al. (2021) highlighted that participants found the VR experience more user-friendly, natural for interaction, engaging, and effective for visualizing concepts such as sorting algorithms. The results suggest that VR settings enhance presence, absorption, flow, psychological immersion, and positive emotions compared to traditional desktop settings when learning sorting algorithms. This indicates that integrating VR into computer science education can offer new forms of interaction with visualizations and foster motivational, emotional, and perceptual factors that positively impact the learning process.

Additionally, Srimadhaven et al. (2020) noted that computer science courses, including those on algorithms, mathematics-related algorithms, and programming languages, often present significant challenges for students. VR can help address these difficulties by providing real-world and hands-on experiences in a safe environment. This approach facilitates understanding complex concepts and promotes active engagement in cognitive learning.

Furthermore, Oleksiuk (2020) suggested that AR has the potential to enhance computer science education by enabling students to observe computer systems, modify hardware, and visualize algorithms and data processing. AR can increase research realism, provide emotional and cognitive experiences, engage students in systematic learning, and create new opportunities for collaborative learning and the representation of the real objects.

As shown in **Figure 6**, AR and VR applications in education are predominantly concentrated in STEM disciplines, followed by physics, language learning, history, geography, computer science, and other subject-specific domains.

Critical Synthesis and Literature Gaps

A critical synthesis of the 53 reviewed studies revealed both promising applications and notable limitations in the current body of literature. This synthesis highlights the research gaps, identifies the

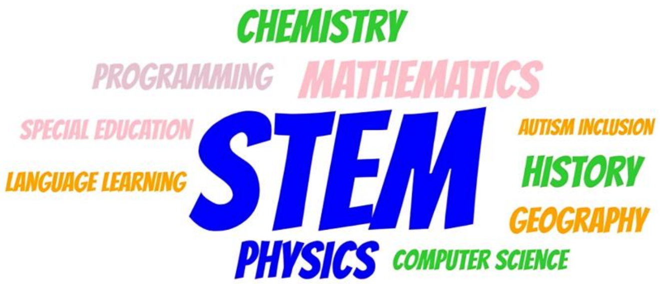

Figure 6. Thematic word cloud of AR and VR application domains in education (Source: Authors' own elaboration, using https://wordart.com/)

conditions under which AR and VR are most effective, and clarifies the context in which their impact is less effective, thereby providing a bridge to the discussion section.

Limitations and gaps in the literature

1. Few studies have assessed the long-term impacts of AR and VR on student learning outcomes and retention.
2. Research has concentrated on STEM disciplines, whereas areas such as arts, social sciences, humanities, and language education remain underexplored.
3. Accessibility barriers persist, particularly in low-resource contexts, due to the high cost of hardware, infrastructure limitations, and ongoing maintenance requirements.
4. The lack of teacher training and the absence of well-developed pedagogical frameworks continue to hinder the effective integration of AR and VR technologies in formal education.
5. Few studies have examined the ethical and health implications (e.g., motion sickness and eye strain) in real learning environments.

The reviewed studies indicate that AR and VR technologies are most effective in experiential, interactive, and collaborative learning environments, particularly within STEM disciplines, such as science, technology, and mathematics. These technologies excel in visualizing complex concepts, supporting problem-based learning, and enhancing students' motivation and engagement. AR is especially effective for overlaying digital content onto real-world settings, fostering situated learning, while VR enables fully immersive experiences such as virtual field trips and laboratory simulations. Applications involving the visualization of complex 3D content, including anatomy, molecular structures, and geometric shapes, consistently demonstrate the highest learning gains.

Despite their potential, AR and VR have shown reduced effectiveness in contexts with technical or logistical barriers. High equipment and maintenance costs, limited infrastructure, and software usability issues hinder large-scale adoption. Studies have also highlighted that inadequate teacher training and the absence of clear pedagogical frameworks limit the meaningful integration of these tools. Moreover, health-related concerns such as eye strain and motion sickness can negatively affect prolonged usage, particularly in younger learners.

This synthesis underscores the need for further longitudinal studies, broader disciplinary applications, and targeted teacher training, thereby setting the stage for the discussion of practical and research implications in the next section.

DISCUSSION

AR and VR Evolution in Education (2014-2024)

The evolution of AR and VR technologies from 2014 to 2024 highlights a clear trajectory from experimental adoption to widespread integration in education. Early implementations focused on low-cost VR solutions (e.g., Google Cardboard) and simple immersive experiences, while later years saw an increase in interactive simulations, gamification, and mixed reality environments. The recent integration of generative AI with AR and VR has further expanded educational possibilities by offering personalized, dynamic, and adaptive learning experiences.

This progression reflects a shift driven by technological advancements, pedagogical changes, and other ongoing challenges. The transition from basic VR headsets to standalone, AI-enhanced mixed reality solutions has enabled deeper interactivity and realism in educational applications. AR and VR have moved from passive content consumption, such as 360° videos, to active, student-centered learning with simulations, virtual labs, and real-world applications. Despite these advancements, digital equity, accessibility, and teacher training remain crucial for effective large-scale adoption of these tools.

As illustrated in **Figure 2**, this timeline highlights how AR and VR have evolved into powerful tools for enhancing engagement, collaboration, and experiential learning. However, further research, investment in teacher training, and addressing infrastructural challenges will be essential for sustained impact.

Benefits of VR and AR for Education

Integrating VR and AR in education offers remarkable benefits, particularly in enhancing student motivation and engagement. Studies have shown that these technologies increase students' enthusiasm and readiness to participate in class discussions (Al-Ansi et al., 2023; Anuar et al., 2021; Feridun & Bayraktar, 2024; Yildirim, 2020). With their vivid visuals and captivating sounds, the immersive nature of VR and AR cultivates genuine curiosity for subject matter. Moreover, these technologies support students with special needs by fostering a more inclusive learning environment (Al-Ansi et al., 2023). VR also extends education beyond traditional classrooms, enabling distance learning and reaching new demographics (Lege & Bonner, 2020; Ntaba & Jantjies, 2019). Furthermore, VR and AR play a crucial role in enhancing non-cognitive skills such as CT, collaboration, and problem-solving (Hanggara et al., 2024). These technologies create opportunities for students to collaborate in virtual environments, fostering teamwork and communication (Papanastasiou et al., 2019). In addition, AR and VR technologies have shown significant potential in enhancing accessibility and inclusion for students with disabilities by providing tailored learning experiences that cater to individual needs (Asatryan et al., 2023; Mohamed et al., 2024).

In assessing the cost-effectiveness of VR and AR in education, weighing the initial investment against the long-term benefits is crucial. While the upfront costs for VR and AR hardware and software can be high, these technologies offer potential cost savings by reducing the need for physical resources, such as textbooks and lab equipment. For instance, a study by Marks and Thomas (2022) found that the implementation cost per student visit to the VR laboratory at the University of Sydney was only AU$19.50, highlighting the cost-effectiveness of educational investment. The relatively low cost per visit, combined with the reported enhanced learning outcomes, demonstrates that VR technology can offer substantial educational benefits without imposing a significant financial burden on institutions. This finding highlights the potential of VR as a financially viable option for enhancing educational experiences while effectively managing costs. Moreover, the immersive and interactive nature of VR and AR can enhance teacher efficiency by facilitating more engaging and effective lessons, which may improve student outcomes and reduce the need for supplementary educational support.

The benefits identified in this study, including increased student motivation, enhanced engagement, and improved learning outcomes, underscore the potential long-term impacts of VR and AR on educational systems. By fostering a more immersive and interactive learning environment, these technologies support a shift towards student-centered learning approaches. VR and AR facilitate personalized learning experiences and deeper engagement, driving the transition towards teaching methods that emphasize student autonomy and active participation. Leveraging these advantages allows educational systems to adapt more effectively to the evolving needs of learners, thereby promoting a more dynamic and inclusive educational environment.

Challenges to Applying VR and AR in Education

Despite their benefits, the implementation of VR and AR in education is challenging. Developing pedagogical approaches tailored to immersive learning environments is complex (Lege & Bonner, 2020). Financial constraints are also significant, as the cost of the necessary hardware and software can be prohibitive for many institutions (Al-Ansi et al., 2023; Familoni & Onyebuchi, 2024; Lyu et al., 2023; Medvedieva & Yamkovenko, 2024). However, the decreasing costs of AR and VR hardware make these technologies more accessible, suggesting a promising future for their widespread adoption in education.

Usability issues, including software complexity and hardware reliability, present additional hurdles. Accessibility remains a concern, particularly for students who lack the required hardware and software (Al-Ansi et al., 2023). Health considerations, such as discomfort from prolonged use of headsets, add another challenge (Elmqaddem, 2019; Pelin Yildiz & Yildiz, 2022). Additionally, gender dynamics, which may cause discomfort among female students using HMDs, must be considered (Lege & Bonner, 2020).

Ethical Considerations in the Use of AR and VR Technologies in Education

As AR and VR technologies become more integrated into educational settings, it is essential to address ethical considerations associated with their use. Protecting user privacy and data security is paramount, particularly when these technologies are used to collect and process personal information. Additionally, there is a need to consider the potential psychological impact on students, such as the risk of addiction or desensitization due to prolonged exposure to virtual environments. Ensuring that these technologies are used responsibly and ethically requires clear guidelines and governance frameworks, as well as professional training for educators to effectively integrate them into their teaching practices.

Application Domains of VR and AR in Education

VR and AR have been successfully integrated into various educational domains. In STEM education, AR enhances student engagement and learning outcomes by providing visual representations of complex concepts (Ibáñez & Delgado-Kloos, 2018; Sırakaya & Alsancak Sırakaya, 2022). In Physics education, AR and VR technologies enhance learning by converting abstract concepts into tangible experiences and facilitating virtual experiments. These tools promote active learning and improve students' understanding and retention while motivating them to apply physics principles in real-world contexts. Research indicates that mobile AR users achieve better learning outcomes and engagement, especially with complex topics like magnetic fields, making physics education more interactive and accessible (Isma et al., 2024; Prayogi & Verawati, 2024; Rahmat et al., 2023). In Geography education, these technologies offer immersive experiences that enrich fieldwork and geospatial learning (Bos et al., 2022). VR has also proven effective in history teaching through immersive, experiential learning methods (Yildirim et al., 2018). In addition, AR and VR tools facilitate language learning by improving vocabulary acquisition and language skills (Huang et al., 2021).

Integration of AR, VR and Immersive Experiences in Education through the Metaverse

The metaverse concept has recently gained traction across various sectors by offering immersive and interactive experiences that transcend traditional digital platforms. The Meta-Metaverse methodology introduces the potential to create realistic digital twins, which are virtual representations of physical objects, systems, or processes, and has promising implications for AR and VR educational applications. The multi-layered structure of the metaverse enables enhanced flexibility and scalability, thereby providing unique opportunities for immersive learning environments (Jamshidi et al., 2023).

In education, digital twins can be applied to simulate complex systems (e.g., biological models and historical settings), allowing students to interact with these virtual representations in real time. This level of interaction can significantly enhance student engagement and knowledge retention by offering realistic simulations that are often impossible in traditional classrooms. The potential of metaverse technology in education aligns with AR and VR goals by making learning more interactive, personalized, and impactful. Furthermore, as suggested by the meta-metaverse methodology (Jamshidi et al., 2023). These technologies offer scalability and flexibility, enabling educators to tailor experiences to different learning styles and needs.

Moreover, integrating digital twins into the metaverse offers significant potential for enhancing educational experiences with AR and VR. By creating accurate digital representations of real-world components, digital twins bridge the gap between physical and virtual environments (Jamshidi et al., 2024). This approach not only enriches communication systems but also fosters immersive learning opportunities. These findings suggest that employing an intelligent digital twinning approach can advance the metaverse's development (Jamshidi et al., 2024), facilitating deeper engagement and understanding in educational contexts.

CONCLUSION

The integration of AR and VR into educational settings has demonstrated substantial benefits, including enhanced motivation, engagement, and improved learning outcomes. These technologies address previously inaccessible educational situations and support diverse learning needs through immersive experiences, as shown in disciplines such as STEM, geography, language learning, and computer science. Looking forward, AR and VR are poised to significantly reshape educational practices as tools become more sophisticated and accessible. Emerging developments, including the metaverse concept, may enable realistic simulations and personalized, adaptive learning environments in which students interact with rich, dynamic content in unprecedented ways.

However, their sustainability and widespread adoption require addressing key challenges such as equitable access, high implementation and maintenance costs, the need for regularly updated educational content, and ongoing teacher training.

In the long term, AR and VR have the potential to transform both learning processes and institutional operations, fostering CT, problem-solving, and lifelong learning. Realizing this potential will depend on collaboration among educators, policymakers, and researchers to overcome barriers and fully leverage these transformative tools for equitable educational opportunities.

To advance the field, the following steps are recommended:

1. **For researchers:** Conduct longitudinal studies to evaluate the long-term impacts across diverse disciplines, including underexplored areas such as the arts, humanities, and social sciences.
2. **For educators:** Engage in targeted professional development to effectively integrate AR/VR into curricula and align usage with sound pedagogical frameworks.
3. **For policymakers:** Develop funding models and infrastructure policies to ensure equitable access, particularly in low-resource contexts.
4. **For developers:** Prioritize usability, accessibility, and content relevance to meet the needs of diverse learners, collaborating with educators to produce impactful learning tools.
5. **For institutions:** Explore blended approaches combining traditional and AR/VR-based learning, supported by partnerships with technology companies to share resources and infrastructure.

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APPENDIX A

Table A1. Overview of reviewed studies including authors, publication year, country, and research methods

No	Reference	Country	Methods
1	Al-Ansi et al. (2023)	Yemen	Literature review
2	Almazaydeh et al. (2016)	Jordan	Experimental
3	AlNajdi (2022)	Saudi Arabia	Semi-experimental
4	Anuar et al. (2021)	Malaysia	Quantitative
5	Arici et al. (2019)	Turkey	Literature review (bibliometric)
6	Asatryan et al. (2023)	Armenia	Literature review (narrative with case examples)
7	Familoni and Onyebuchi (2024)	United States	Literature review (narrative)
8	Bertrand et al. (2024)	Canada	Qualitative case study
9	Bos et al. (2022)	United Kingdom	Multi-case study/qualitative
10	Boyles (2017)	United States	Literature review
11	Çetin and Türkan (2022)	Turkey	Single-group pre-/post-test experimental design (quasi-experimental)
12	Dhagare (2024)	India	Conceptual literature
13	Diegmann et al. (2015	Germany	Systematic literature review
14	Elmqaddem (2019)	Morocco	Comparative conceptual analysis
15	Feridun and Bayraktar (2024)	Turkey	Comprehensive literature review
16	Hamad & Jia (2022)	United States	Literature review
17	Hanggara et al. (2024)	Indonesia	Quantitative (quasi-experimental)
18	Huang et al. (2021)	China	Systematic review
19	Ibáñez and Delgado-Kloos (2018)	Spain	Systematic review
20	Isma et al. (2024)	Indonesia	Research and development (R&D)
21	Jamshidi et al. (2023)	Czech Republic	Conceptual framework
22	Jamshidi et al. (2024)	Czech Republic	Experimental
23	Kavanagh et al. (2017)	New Zealand	Systematic review
24	Lege and Bonner (2020)	Japan	Literature review
25	Leonard and Fitzgerald (2018)	Australia	Mixed
26	Lytvynova and Soroko (2023)	Ukraine	Mixed
27	Lyu et al. (2023)	China	Mixed methods (co-design + field experimental study: Quantitative & qualitative)
28	Marks and Thomas (2022)	Australia	Experimental
29	McNamara et al. (2016)	United States	Experimental
30	Medvedieva and Yamkovenko (2024)	Ukraine	Literature review
31	Mohamed et al. (2024)	Morocco	Literature review
32	Ntaba and Jantjies (2019)	South Africa	Systematic literature review
33	Oleksiuk (2020)	Ukraine	Experimental
34	Papanastasiou et al. (2019)	Greece	Literature review
35	Pears et al. (2020)	United Kingdom	Conceptual
36	Pelin Yildiz and Yildiz (2022)	Turkey	Mixed
37	Pirker et al. (2021)	Austria	Experimental
38	Pradana and Elisa (2023)	Indonesia	Systematic literature review
39	Prayogi and Verawati (2024)	Indonesia	Literature review
40	Rahman et al. (2022)	Bangladesh	Systematic review
41	Rahmat et al. (2023)	Indonesia	Mixed
42	S M et al. (2016)	India	Experimental
43	Safar et al. (2017)	Kuwait	Experimental
44	Sala (2020)	Italy	Literature review
45	Sarkar and Pillai (2021)	India	Qualitative
46	Schutera et al. (2021)	Germany	Experimental
47	Sırakaya and Alsancak Sırakaya (2022)	Turkey	Systematic review
48	Srimadhaven et al. (2020)	India	Experimental
49	Yáñez et al. (2015)	Spain	Qualitative
50	Yildirim, (2020)	Turkey	Mixed
51	Yildirim et al. (2018)	Turkey	Case study
52	Yilmaz and Coskun Simsek, (2023)	Turkey	Qualitative
53	Zallio et al. (2024)	United Kingdom	Scoping review