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Extended Reality in STEM: A Modernised Educational Tool for Children

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Review Article

Abstract:
For many years, researchers argued that Extended Reality (XR)—an umbrella term that refers to all immersive technologies—has the potential to revolutionise early years education by providing new and innovative ways for children to learn. Specifically, XR is suggested as a powerful tool in Science, Technology, Engineering, and Math (STEM) education. By blending the physical with the virtual, the creation of unique multisensory environments with XR has been shown to deliver hands-on learning experiences that exceed outcomes from traditional teaching. Nevertheless, the high cost, limited content, technical challenges, and lack of teacher training constrain the prevalence of XR in STEM education. In this article, we discuss the key strengths and limits of XR in education, review recent advances in its use in STEM disciplines, and point to future directions for how XR should be integrated into the school curriculum to facilitate children's outcomes in STEM education.

Keywords: Extended reality; Education; STEM education; Virtual reality; Technology in education

1. INTRODUCTION

The use of technology in education has been a topic of discussion for decades. Many educators use technology in their classrooms to varying degrees which depend on numerous factors such as the available resources, the type of technology, and the individual preferences or skills of the educators themselves. The adoption of technology has been uneven in different parts of the world and across different educational contexts (1). In the last decade, the use of technology in education has accelerated rapidly with advancements in internet penetration, the emergence of online learning platforms, and the move towards digital teaching during the COVID-19 pandemic.

Extended Reality (XR)—an umbrella term that refers to all immersive technologies—is a central topic of discussion about technology in education (2). XR offers an opportunity to interact with landscapes and resources which are otherwise constrained due to cost or logistical factors (3, 4). From its early iterations in Sutherland et al's "Sword of Damocles" (5) to more recent, interventional uses in education (6), the learning gains associated with XR were first indicated in the late 20th Century.

In this article, we review the current landscape of XR in Science, Technology, Engineering, and Math (STEM) education. We begin by characterising types of extended reality, continue with the strength and limitations of XR in education and elaborate on the latest advances in using XR to promote STEM learning. We conclude by pointing to future directions for the development of XR-based educational intervention.

2. TYPES OF EXTENDED REALITY

XR includes three different ways to present information to its users: Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These are not mutually exclusive and can be used in combination to create a wide range of experiences. Additionally, the technology and hardware behind VR, AR, and MR are constantly evolving, so the distinction between these types of XR is fluid and some researchers may use different definitions for the same technology. XR as a uniting field of these technologies is relatively new and defining the different types of XR technologies is an ongoing debate.

2.1 Virtual Reality

VR allows users to interact naturally with digital environments on monitors or using head-mounted displays. The concept of VR technology is not new; the first iterations of helmet-mounted displays and visually coupled systems being employed in 1966 in US Air Force training (7). However, only in the last two decades, its value for child education has been investigated. Developmental studies tested VR in educational intervention to improve learning factors including attention duration, student enjoyment, and deeper understanding (8, 9). Although VR was shown to be effective, it was not widely

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adopted due to a lack of quantitative data on educational outcome improvements and high-cost implications for schools (8, 10).

2.2 Augmented Reality

AR relies on the superimposition of virtual objects onto the user's natural environment (10), creating a bridge between real and artificial worlds. AR was identified as a key emerging technology in education (11) following the successful use of handheld and mobile computers in environmental simulations (12) and primary school science (13). Typically, AR technology is either marker-based, where scanning a marker within a static image triggers an augmented response visible on a hand-held device, or markerless-based, relying on a combination of GPS, a compass and some form of image-recognition device (e.g. a camera on a mobile phone) (14). Over the years, AR has been embedded successfully in various academic disciplines including astronomy, chemistry, biology, and literacy, Due to the mobile nature of the technology, AR has also been implemented in cultural sites (15, 16) and museum tours (17), with great benefit to the audience.

2.3 Mixed Reality

MR is a more recent technology that combines AR and VR. MR creates a fully immersive digital experience, similar to VR, in which the user is completely surrounded by a computer-generated environment. MR also superimposes digital information onto the user's view of the real world, as in AR. MR differs from the other two XR technologies by creating a blend of virtual and physical worlds in which digital information is seamlessly integrated with the user's physical environment. MR can be thought of as a continuum where VR is a complete virtual immersion and AR is a complete physical immersion, while MR sits somewhere in between, depending on the specific application and technology used. MR is not broadly seen in education due to the inaccessible cost. Recent studies in university anatomy classes showed that compared to standard cadaver-based learning, MR technology leads to improvements in retention, faster learning, and better responses from students (18).

3. XR IN EDUCATION: STRENGTHS AND LIMITATIONS

3.1 Educational Flexibility

One of the key strengths of XR is the teaching flexibility it allows. In traditional education, students are often confined to a physical classroom and must learn at a pace that is set by the teacher. With XR, however, students can access digital content from anywhere and at any time, allowing them to learn at their own pace (19). This is particularly beneficial for students who are unable to attend traditional classes, such as those who live in remote areas or have mobility issues. This accessibility opens more opportunities for learners, making education more inclusive and equitable (20, 21). This flexibility is true for many educational technologies, especially during the Covid-19 era, where online and hybrid study structures became a norm. All more so for XR because the combination of the virtual with the physical yields a unique experience. Virtual field trips (22), for example, allow students to "visit" a location or experience an event without ever leaving the classroom. This allows novel accessibility where students visit places that might be too far or too expensive, such as museums, historical landmarks, or natural habitats all over the world (22, 23). XR also allows more flexibility than other technologies because it can be customised to the class type. For example, a virtual field trip to a museum might be tailored to a history class, whilst one to a space centre might be designed for a science class.

The educational flexibility of XR was also found useful when instructing students with certain disabilities or additional learning needs (24). These students can experience digital content in a way that is tailored to their individual needs. For example, students with dyslexia could use AR to view text in a font that is easier for them to read, or a student with ASD might use VR to practice their social skills in a controlled environment. This customisation allows more students to participate and enhances the effectiveness of individual interventions.

In addition to flexibility in where to learn, XR provides flexibility in how to learn. Students traditionally rely on static text, images, or videos to understand concepts or learn new skills. Yet, students' interaction with XR content is more embodied, natural and intuitive, especially when complex concepts are visualised (25). Students can explore the inner workings of a cell in a VR biology lesson by manipulate it with their hands, or students can see historical sites and artifacts overlaid in the real world in an AR history lesson, allowing them to make connections to their own experiences. This level of interactivity and engagement leads to deeper understanding and better retention of information (2). These beneficial interactive simulations can also be used to confront students with real-world scenarios that would be difficult or impossible to replicate in the classroom. Students studying engineering can use a VR simulation to design and test a bridge in a virtual environment, while students studying architecture might use an AR app to visualise a building design in the real-world.

3.2 Ecological Validity

A major challenge in educational research is to maintain ecological validity—a measure of how well an experiment reflects the natural conditions of the environment being studied. The relevant ecologically valid methodologies in educational research are naturalistic observations or field studies (26). These take place in the natural environment of individuals (e.g. in schools for school-age children) and therefore the behaviours and interactions observed are more likely to reflect what occurs in real-life situations, as opposed to artificially constructed laboratory settings that may not accurately represent the typical learning context. However, those studies are often time-consuming, may require additional ethical considerations (e.g. avoiding disruption of students' education), and researchers may not have as much control over other variables which

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may influence the behaviour being studied. Finally, conditions in natural settings tend to be unpredictable, making it difficult to plan and conduct the experiment.

XR creates highly realistic and immersive virtual environments that closely mimic real-world situations. Thus, using XR in a controlled experiment provides high ecological validity without many of the limitations that exist in naturalistic experimentation. Such “realism” supports researchers’ efforts to ensure that educational studies are applicable to educational contexts (27, 28). This realism enhances physics education by discovering new environments, developing experiences, constructing hypothesises, and analysing the end results (29). Taken together, VR environments leads to increased imagination, associations, understandings, and local judgements (30).

3.3 Embodied Education

Physical and social context has a significant role in education (31). Learning does not take place solely in the mind and cannot be isolated from the body, environment, and interactions (32-34). Children’s physical and social surroundings provide a context for learning that shapes how they perceive, process, and apply knowledge. Education, therefore, is embodied (35-37). Teachers who support the concept of embodied education use activities such as hands-on experimentation, movement-based learning, and immersive experiences that engage multiple senses.

XR is a framework for embodied education because it allows children to fully immerse themselves in the teaching materials and interact with them physically. For example, researchers developed an AR sandbox which allows children to learn about topography and watersheds by shaping a virtual landscape with real sand. The sandbox increased children’s engagement and understanding of scientific concepts (38). Similar improvements were shown when children learned anatomy (39) and physics (40, 41). The interactive and engaging XR experiences allow children to manipulate virtual objects in three-dimensional space, see objects from different angles, and visualise abstract concepts in a more concrete way.

3.4 Limitations

As with any new technology, teachers, educators, and administrators are required to practice effective XR in their curriculum. The current literature demonstrates several limitations in understanding the different applications and potential effectiveness of VR technology in educational contexts (42). First, there is a debate regarding whether XR is intended to replace existing successful teaching approaches or to supplement and enhance current methods, and therefore, it should be considered complementary to traditional methods (42-44).

Another downside that cannot be overlooked is the fact that much like any computer technology, virtual reality devices are susceptible to breakdowns or crashes, and this risk escalates as more students engage with these devices (18, 45). To address this concern, educators and researchers realise that having backup devices readily available is critical, and contingency lesson plans must be in place to tackle technical issues, internet disruptions, or any unforeseen circumstances that might impede the seamless use of virtual reality in the classroom (43). Scientific research does not address this issue at the moment.

Finally, embodied use of XR when surplus to requirements could create its own problems. Some participants in virtual reality studies have reported feelings of nausea, motion-sickness, or minor headaches while using the devices (46). In one particular study, the incidence of these discomforts reached as high as 10-20% of users (47). Educators must be mindful of these potential side effects and take necessary measures to minimise any adverse impact on students' health and overall learning experience.

4. ADVANCES IN XR AS A TOOL IN STEM EDUCATION

STEM education is critical in a structured curriculum. Governing bodies worldwide invest significant resources into the development of STEM-specialist teachers, broader curricular enrichment projects and building STEM charities into supportive bodies for educators (48). As a result of this focus shift, a large body of education technology (EdTech) including the G Suite for Education, online simulations, and gaming as an instructional tool (49, 50) have also been developed to facilitate growth in this sector. Many meta-analyses and systematic reviews (8, 51-60) discussed the educational use of VR and AR. Nonetheless, the majority of these publications preceded the advancements in technology quality and cost reductions. The key focus of this section will be examining the advances and current uses of XR within STEM education from four perspectives: Literacy, developing and training spatial skills, enhancing mathematical capabilities and finally collaborative learning—the ability for students to interact and engage with each other within a virtual space. The current literature demonstrates the transformative potential of XR within STEM education, highlighting quantitative and qualitative outcomes that motivate its use.

4.1 Literacy

STEM literacy, encompassing the knowledge and skills required to understand and address problems in STEM fields, has been acknowledged as a critical competency for educational success (61-63). Early attempts at using XR for STEM literacy primarily focused on addressing technical challenges, and examples include AR curricula such as "Alien Contact!" and "Gray Anatomy," and desktop virtual-reality software for engineering and technology literacy (64-66). While these initiatives incorporated STEM content and fostered student engagement, they were constrained by technological limitations and required extensive teacher involvement.

With technological advancements, more recent studies have explored the potential of XR to promote STEM literacy among young learners (67). Findings show that XR offers diverse advantages regarding authentic target literacy

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assessment, fostering interactive experiences, boosting motivation, enhancing task engagement, facilitating vocabulary acquisition, and promoting cultural learning (67). Additionally, it has proven effective in reducing foreign language anxiety levels. Other virtual worlds, such as those developed in OpenSimulator, contribute to the development of communicative competence and learner autonomy, creating a sense of immersion and presence, and enabling collaborative exchanges (67-71). Taken together these findings are supported by a recent meta-analysis that shows statistically significant improvement in students' test scores, with an effect size of 0.45, in literacy tests (72).

However, recent findings reveal two critical limitations across various types of XR: unstable technical issues (68) and a lack of sufficient multimodal resources (73). For instance, researchers examined story delivery for 3-year-olds using AR and interactive e-books (74). Although AR technology increased interest in reading, literacy gains were similar to those found in traditional paper-based formats. Moreover, AR diverted students' attention towards the technology itself rather than the story content (74). In another study, students were randomly assigned to two groups: one using AR and the other using iPads for literacy learning. The results showed no significant differences in literacy assessments between the groups, indicating that AR doesn't outperform other technologies like iPads in enhancing literacy learning (75). Taken together, while XR technologies can enhance engagement in research settings, their potential in fostering deeper literacy outcomes should be considered carefully in educational settings.

4.2 Spatial Skills

Embodied education allows children to develop their spatial skills in a natural and intuitive way. Playing with blocks, building with Legos, and drawing in 3D are all examples of embodied learning activities that require learners to manipulate objects in space and visualise them in three dimensions. Previous educational work showed that XR facilitates children’s spatial skills (76) and may have an advantage over real-world embodied education (32). XR technologies also provide children experiences that help to develop spatial awareness—the ability to perceive and understand the relationships between objects in space—by interacting with virtual objects and seeing how they relate to their surroundings in real time. For example, children who use XR to explore a virtual solar system have improved spatial awareness compared to those who explore a physical solar system (77, 78). More broadly, children who learn science concepts through XR have improved spatial reasoning skills compared to those who used traditional methods because they visualise and interact with abstract concepts in a more concrete and intuitive way, which enriches their ability to reason spatially (79).

A multifaceted aspect of human intelligence (80, 81), spatial ability relates to both static and dynamic factors including static visual memory, directional judgement, and spatial orientation (82). Longitudinally, strong spatial skills in adolescence are linked to later progression and successes in STEM-related careers (83-85), and, encouragingly, spatial skills are also responsive to interventions and training, resulting in educational enhancements (82). As a result, XR in the age of information provides ample opportunity to enhance STEM outcomes in students (6, 86, 87).

The use of XR and virtual environments in spatial training have been studied since the turn of the century. Virtual environments were used as part of mental rotation training resulted in greater improvements in post-training mental rotation test scores compared to those who used traditional learning tools. Subsequently, XR tools have been extensively tested within various educational settings, highlighting moderate improvement in test scores compared to other teaching and learning technologies (8, 88-91). Despite these findings, spatial abilities and STEM within a school environment is limited due to inaccessibility of resources and poor technological literacy of staff (6, 92, 93). When young children use AR during free play, active engagement with virtual overlays in typical learning environments enhanced their use of descriptive spatial language (e.g. curved, straight, here, there) for both static and dynamic objects (94). A meta-analysis of the impact of VR technologies on students’ spatial abilities indicated that, rather than older children and adolescents, younger children of preschool age improved when they used virtual-based learning tools compared to other age groups (95).

In older children, other spatial skills such as mental rotation improved with XR training. For example, VR environments for teaching biology increased adolescents’ perceived control on objects (i.e. the subjective belief regarding their ability to manipulate objects), improved spatial rotation and angular geometry (96). VR also increased self-perception, and later enhanced spatial and mental rotation results on cognitive tests within the same study. Spatial visualisation is another key spatial skill for STEM learning. Using head-mounted displays in geometry education using novel Construct3D software was promising, with participants citing that the ability to actively engage and move around within 3D objects was both supportive and enjoyable (97, 98), resulting in enhanced visualisation ability.

4.3 Maths

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As an important component of human intelligence (80, 81), spatial ability relates to static and dynamic factors including visual memory, directional judgement, and spatial orientation (82). Longitudinally, strong spatial skills in adolescence are linked to later progression and successes in STEM-related careers (83-85), and, encouragingly, spatial skills are also responsive to interventions and training, resulting in educational enhancements (82). As a result, XR can enhance STEM

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outcomes in students through its effects on spatial skills (6, 86, 87). This has been shown since the turn of the century. Virtual environments were used as part of mental rotation training, which resulted in greater improvements in post-training mental rotation test scores compared to those who used traditional learning tools (8, 88-91). VR environments in biology classes also improved adolescents' self-perception (e.g. the subjective belief regarding their ability to manipulate objects), spatial rotation and angular geometry (92). Finally, after using head-mounted displays in geometry education using novel Construct3D software, participants also reported that actively engaging and moving around within 3D objects was both supportive and enjoyable (93, 94), resulting in enhanced visualisation ability.

The effect of XR on spatial skills are not limited to older children or adolescents or to mental rotation tasks. When young children use AR during free play, active engagement with virtual overlays in typical learning environments enhanced their use of descriptive spatial language (e.g. curved, straight, here, there) for both static and dynamic objects (95). A meta-analysis of the impact of VR technologies on students' spatial abilities indicated that, rather than older children and adolescents, younger children of preschool age improved when they used virtual-based learning tools compared to other age groups (96). Nevertheless, similar studies and reviews argue that improvements in spatial abilities within an early school environment is limited due to lack of accessibility to resources and poor technological literacy of staff (6, 97, 98).

4.4 Collaborative Learning

From online medical appointments (99) to 'visiting' geographical landscapes during the COVID-19 pandemic (100), XR in STEM education has afforded opportunities for individuals to connect and collaborate online, working together without physically being together. Specific research into the benefits of XR in collaborative learning is in its relative infancy. However, some studies highlighted its benefits for collaborative learning. In recent years, collaborative learning has emerged as a salient and evolving pedagogical approach that holds increasing importance within the context of modern classrooms (101, 102). This approach draws substantial scholarly attention, driven by its potential to revolutionise traditional educational practices and enhance student outcomes. The essence of collaborative learning lies in its capacity to engender cooperative group dynamics while fostering essential interpersonal skills and advanced cognitive abilities (101). Empirical research and theoretical analyses underscore the benefits of this educational model, highlighting its role in promoting active engagement, knowledge construction, and critical thinking among students (102-104).

Work in the early 2000s identified the potential utility of AR in collaborative learning (105, 106). This line of research intensified as the Covid-19 pandemic forced educators to employ, test and evaluate XR tools to maintain student attitudes to learning at home. Studies using XR in prosocial tasks (where the welfare and needs of others must be considered) showed improvements in communication and problem-solving abilities through use of 'good inequality' (107). This is where grouped participants are given different tools to use (e.g. tablet or head-mounted unit), each with its own strengths and limitations within the same setting and have to work together to achieve a common goal (108, 109).

In virtual learning environments, collaborative communication between all parties (teacher-student, instructor-student, and student-student groups) enhances learning attitudes and learning experiences in various XR paradigms (110, 111). This benefit also extends to domain-specific improvements including maths (112-115), biology (116-118) and geography (110, 119). In traditional classroom settings, XR is also seen to enhance collaborative learning by providing engaging experiences that represent real-world phenomena and processes more authentically and accurately than traditional teaching tools such as interactive whiteboards (6).

5. PUSHING THE ENVELOPE: THE FUTURE OF XR AS A TOOL IN EDUCATION

The reviewed research clarifies the need to provide a more detailed understanding of the educational contribution of XR to STEM (4). We believe that the future of educational XR will depend on the expansion of the technology, scale of innovation and developments in learning approaches. To support this, we propose key areas of focus for future educational research. First, existing research regarding the true advantage of XR remains cloudy. The prevailing question concerns whether the benefits are solely attributable to heightened student engagement or whether the embodied experience in XR genuinely enhances the learning process (120). That is, whether learning with XR is grounded in students' bodily interactions with the environment (121, 122). By scrutinising the neurological responses and cognitive processes triggered by XR immersion, future research should elucidate the information processing, knowledge retention, and skill acquisition within these virtual environments to understand whether STEM education is refined through immersive sensory-motor feedback. For example, how does the level of immersion in XR environments impact knowledge acquisition and retention in STEM? What is the effect of the immersive feedback on trial-and-error learning and how does it differ from traditional instructional methods? Using designed experimental paradigms is necessary to address these questions.

Along with testing the contribution of embodiment, the trajectory of future research should centre on the realm of personalisation, seeking to ascertain how customised XR experiences contribute to educational outcomes. By tailoring XR applications to the individual learner's cognitive skills, prior knowledge, and learning preferences, researchers model the potential added value of personalisation (123-125). Rigorous investigation in this domain must involve longitudinal studies and both quantitative and qualitative assessments (126).

Pushing the envelope of XR as a transformative educational tool should also focus on teacher training and pedagogical integration. Research has shown that providing educators with targeted professional development on XR technologies enhances their confidence and competence in incorporating XR into the STEM curriculum (127, 128). Yet, most studies examined the use of XR to teach teachers (129) with specific focus on pre-service teachers, most commonly using instructional simulations (129). Less efforts were done to develop an optimal training program to equip STEM educators with XR expertise. Such programs should build on interactive sessions that showcase XR simulations of complex scientific phenomena, allowing teachers to delve into abstract concepts and visualise intricate processes. Educators should receive

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guidance on how to align XR experiences with established STEM curricula effectively and how to harness XR to foster a passion for scientific discovery. XR should be the means and not the goal.

Finally, it remains to be seen if integration of XR into collaborative learning environments can influence group dynamics and problem-solving skills in STEM disciplines. Studies reviewed here remain narrow in focus, dealing mainly with student engagement in a virtual space to improve distance learning. Extension of these findings to complex human interactions in education (130), shared virtual environments (131), and teacher-student communications (132) is needed.

Looking ahead, the integration of XR in STEM education is likely to be influenced by advancements in technology affordability and accessibility. As XR devices become more cost-effective, and as content becomes more diverse and tailored, their adoption is expected to rise, potentially becoming a standard feature in educational institutions globally. Based on current adoption rates and technological advancements, XR might be as commonplace in classrooms as computers are today. This projection is based on the compounded annual growth rate of XR technology adoption in educational settings, which has been estimated at 30% over the past three years. Table 1 provides a summary of key references used in this review.

Table 1. Summary of key references on the use of XR as a modernised educational tool.

Topic Key Findings References	**Topic Key Findings References**	**Topic Key Findings References**
Foundations of XR	XR technologies	(5, 7, 29)
Technological	Advancements in XR highlights recent innovations that enhance XR's effectiveness and expand its educational applications.	(2, 4-7)
XR in STEM education.	Education XR technologies significantly improve engagement and outcomes in STEM.	(8, 21, 59, 60)
XR in environmental and cultural education	AR supports experiential learning in environmental and cultural settings, enhancing interaction with the subject matter.	(12, 14-16, 21)
XR in special education	Demonstrates XR's ability to provide adaptable learning experiences tailored to diverse learner needs.	(18, 24, 25, 33)
Virtual field trips and global accessibility	XR facilitates virtual field trips, providing novel access to global locations, thereby enhancing educational inclusivity.	(21-23, 58)
XR for practical skills and simulations	XR is used effectively for simulations and training in practical disciplines such as medicine and engineering.	(27, 57, 112, 116)
Challenges in XR adoption	Discusses technical, financial, and infrastructural barriers to the widespread adoption of XR in education.	(4, 35, 55)
Ecological validity in educational research	XR's use in research offers realistic and controlled settings that maintain high ecological validity.	(26-28, 31)
Collaborative learning with XR	XR enhances collaborative and interactive learning environments, supporting group work and remote education.	(11, 89, 129, 131)
Policy and future directions in XR education	Analyzes policy implications and future educational trends influenced by XR, advocating for strategic educational reforms.	(6, 11, 16, 48, 116)
Neurological and cognitive impacts of XR	XR Investigates how immersive XR environments affect cognitive development and learning processes.	(33, 121-123)

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

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