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Enhancing Education through Leveraging Spatial Computing: A Conceptual Framework

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Abstract:

Traditional teaching practices are often characterized by passive learning, limited interactivity, and a lack of real-time contextual feedback, which struggle to meet the evolving expectations of 21st-century learners. These limitations hinder learner engagement, knowledge retention, and the development of critical thinking skills. In response to these shortcomings, educators have increasingly explored innovative technologies. Among them, Spatial Computing stands out for its ability to merge physical and digital environments, enabling immersive, hands-on learning that traditional tools like video lectures or slide-based content cannot provide. This systematic literature review analyses 16 peer-reviewed studies published between 2020 and 2025, selected from Google Scholar, IEEE Xplore, ScienceDirect, and Springer. It investigates Spatial Computing's educational applications, benefits, challenges, and the technologies supporting its use. The findings reveal that Spatial Computing bridges virtual and reality, thus making learning content multidimensional. This leads to higher retention, active learning, and critical thinking. The findings report on both the great challenge and opportunity of making Spatial Computing available for learning environments. On one hand, it enables interactive simulation learning environments, real-time visualizations of information, and in-the-sim empirical manipulation of objects. On the other hand, it is limited by challenges associated with prohibitively expensive development costs, technical sophistication, and calls for comprehensive evaluation methodologies, inhibiting wide uptake.Additionally, this research highlights the necessity of close interdisciplinarity and the application of sound design methodologies to effectively leverage Spatial Computing. Overall, the review substantiates that Spatial Computing has the promise of radically overhauling conventional education through interactive, immersive, and personalized learning experiences. Future research needs should focus on simplifying the complexities of technology implementation, optimizing the system's design, and developing benchmarked standards for evaluating the learning effects of Spatial Computing.

Keywords: *Augmented Reality, Collaborative Learning, Extended Reality, Mixed Reality, Spatial Computing, Virtual Reality*

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Introduction

The traditional teaching and learning of spatial-dependent disciplines, such as architecture, engineering, and STEM education, rely on two-dimensional materials, including textbooks, diagrams, and lectures. These media may not accurately represent depth, scale, or true-to-life spatial relationships, which are critical factors in developing spatial reasoning (Merino et al., 2020). This limitation is particularly problematic in fields that rely on 3D form, structure, or motion as a core component of understanding. Additionally, the lack of physical labs, models, and collaborative spaces, particularly in low-resource areas, restricts hands-on, immersive learning (Prabhakaran et al., 2022). Mapfumo et al. (2024) argue that these limitations impede student attachment, serving, and retention. These problems make a strong argument for exploring the use of Spatial Computing (SC) to simulate, visualize, and interact with 3D content in ways that media cannot offer. The COVID-19 pandemic further amplified these pedagogical constraints as learners were forced into remote, often offline, learning contexts with minimal interactivity and limited support structures (Mutunhu et al., 2023). Spatial Computing can potentially address this need by providing 3D, computer-generated virtual classrooms. Previous works by Mutunhu et al. (2023) developed a framework to facilitate the move towards virtual-based learning using tools for Spatial Computing and articulated how VR and AR tools could replicate classroom experiences and maintain student interest in times of disruption. Spatial Computing is an umbrella term that encompasses augmented reality (AR), virtual reality (VR), mixed reality (MR), and extended reality (XR), showcasing transformative potential by fusing physical and digital environments to create adaptive, interactive learning ecosystems (Balakrishnan et al., 2021). VR enables students to conduct hazardous experiments safely in simulated labs; the entire digital environment is fabricated, allowing students to perform lab experiments or take virtual tours of museums without requiring any physical materials (Ndlovu et al., 2023). In contrast, AR can be used to project 3D models onto physical machines in real-time (Balakrishnan et al., 2021). Thus, AR layers digital content on top of the real world, such as a 3D model of the human heart over a page in a textbook, allowing students to engage with abstract biological ideas in the moment (Pro, 2024). In addition, MR blends the physical and digital worlds, enabling interactive overlays that respond to the real-world environment, which is especially useful in fields like engineering and medical training (Kıdık & Asiliskender, 2024). For example, wearing a headset and being able to manipulate models of buildings that react to your physical gestures and space(Prabhakaran et al., 2022). Extended Reality (XR) is a meta-term for an immersive technology that comprises VR, AR, and MR. Thus, these XR technologies have different levels of immersion and interactivity potential; hence, they are scalable, environment-based platforms for personalized, interactive learning (Alnagrat et al., 2022).

These technologies allow learners to mould virtual entities, visualize abstract functions, and collaborate on mutual digital terrains, which nurtures deeper engagement and spatial literacy (Chen et al., 2024; Urban et al., 2022). Scholars have explored the use of Spatial Computing in education; however, some critical research gaps remain. AlGerafi et al. (2023) provided a wide evaluation of AR/VR in education but did not offer a taxonomy of tools, on the classifier level, such as Unity. Guo et al. (2021) described extended reality trends but did not analyze barriers to implementation, such as cost or integration into the curriculum. Kıdık and Asiliskender (2024) concentrated solely on mixed reality and architectural pedagogy, without including STEM and vocational trades. Merino et al. (2020) presented MR/AR usability data without quantitative or qualitative data on learning outcomes. Ummihusna and Zairul (2022) showcased immersive environments for learning within architecture without mentioning any collaborative XR frameworks such as Photon Network. Together, these reviews highlight an incomplete understanding of the interdisciplinary possibilities and practical challenges of spatial computing.

To address these gaps, this study presents a Systematic Literature Review (SLR) intending to investigate the technologies and tools, benefits, challenges, and application areas of Spatial Computing in education by addressing the following research questions*:*

RQ1. How are various technologies and tools utilized in implementing Spatial Computing for educational applications?
RQ2. In what ways do Spatial Computing technologies present benefits and challenges in education?
RQ3. How is Spatial Computing applied in different educational settings, and what factors influence its implementation*?*

Methodology

The steps outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses, which include identification, screening, and eligibility, guided the literature analysis for this study (Page et al., 2021).

Search Strategy

A comprehensive search was conducted across multiple academic databases, including Google Scholar, IEEE Xplore, ScienceDirect, and Springer. The search was limited to studies published between 2020 and 2025 to ensure the inclusion of the latest advancements in Spatial Computing. The search strings were constructed using pertinent keywords, synonyms, and Boolean operators to refine results and identify studies related to Spatial Computing in education. The specific search string used was ("Spatial Computing" OR "Augmented Reality" OR "AR" OR "Virtual Reality" OR "VR" OR "Extended Reality" OR "XR" OR "Mixed Reality" OR "MR") AND ("Education" OR "academia"). The search results were as follows: SpringerLink yielded 42 studies, IEEE Xplore yielded 38, ScienceDirect yielded 29, and Google Scholar yielded 167, for a total of 276 studies.

Inclusion and Exclusion Criteria

Studies were included based on whether they were published between 2020 and 2025, written in English, and were peer-reviewed journal articles or conference proceedings. Additionally, the focus of the studies was on the applications, benefits, challenges, and technologies of Spatial Computing in education. Studies were excluded if they were centred on non-educational applications, were not peer-reviewed (such as editorials, grey literature, preprints, or commentaries), fell outside the specified publication period, or lacked empirical data or theoretical relevance. There were no restrictions based on geographical location.

Eligibility and Screening

276 studies were found on four academic databases: Google Scholar (167), SpringerLink (42), ScienceDirect (29), and IEEE Xplore (38). One hundred and ten studies were excluded for duplication and non-relevance in the first phase of screening. The remaining 166 studies underwent abstract and title screening, with a further 112 being excluded due to their irrelevance to the main research question or unclear methodology. Thirty-eight more studies were removed after full-text examination (due to a lack of clear descriptions of mixed reality applications or a lack of educational results). Finally, 16 studies fulfilled the complete inclusion criteria and were included for full-text review.

Included

After a comprehensive assessment of the full texts, only 16 studies met the predetermined inclusion criteria for the systematic literature review. The Prisma flow diagram is depicted in Figure 1.

Results

The delimitation process is illustrated in the following modified PRISMA flowchart, shown in Figure 1, while Table 1 shows a summary of the reviewed articles.

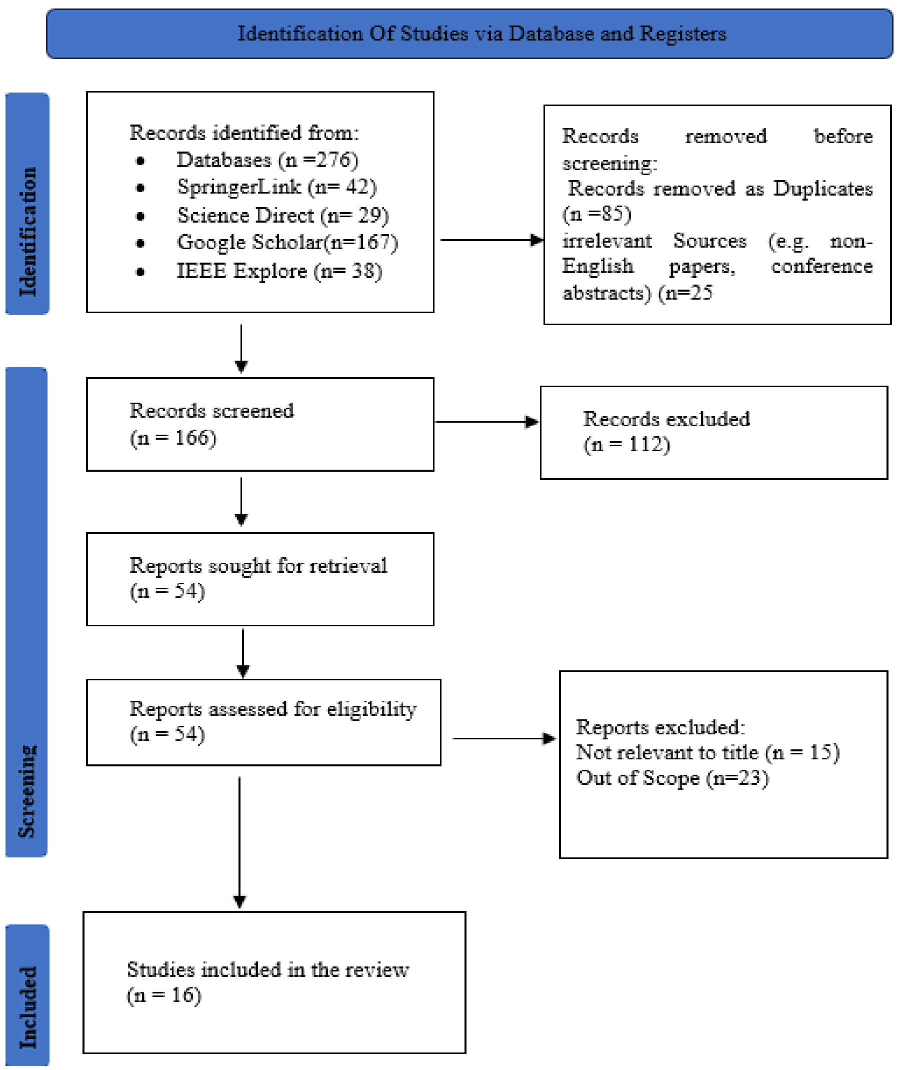

Figure 1. The PRISMA flowchart

Table 1. Reviewed articles

Author (Year)	Origin	Study Setting	Application Area	Benefits	Challenges	Technologies Used	Tools Used	Factors Influencing Implementation
(Elsamahy, 2020)	Egypt	Design Studio	Design Education	Student Engagement	Hardware Limitations	MR	MR Headsets	Design visualization
(Wen et al., 2021)	China	Online Learning	STEM Education	Student Engagement	Hardware Limitations	VR	WebXR WebVR	Accessibility & equity
(Balakrishnan et al., 2021)	India	Engineering Lab	STEM Education	Student Engagement	Hardware Limitations	AR	Google ARCore AR headsets	Cost-effectiveness
(Soliman et al., 2021)	UK	Engineering Lab	STEM Education	Safety	Hardware Limitations	AR/VR	Simulation tools	Remote learning accessibility
(Osorto Carrasco & Chen, 2021)	Costa Rica	Architecture School	Architectural Education	Enhanced Visualization	Technical Complexity	MR	Revit MR Headsets	Design visualization
(Urban et al., 2022)	Austria	Construction Program	Architectural Education	Collaborative Learning	High Costs	VR	BIM Oculus Rift	Collaboration & communication
(Maasthi et al., 2022)	India	Architecture Lab	Architectural Education	Enhanced Visualization	Hardware Limitations	MR	Unity HoloLens	Equity & accessibility
(Das et al., 2022)	Denmark	Architecture Firm	Architectural Education	Enhanced Visualization	Technical Complexity	VR	Unreal Engine Oculus Rift	Technical infrastructure
(Zicheng & Ao, 2023)	China	Design Collaboration	Design Education	Collaborative Learning	Technical Complexity	XR	Photon Network Unity	Collaboration & communication
(Ndlovu et al., 2023)	Zimbabwe	Chemistry Lab	STEM Education	Safety	User Adaptation Issues	VR	Blender Unity VR Headsets	Safety & risk mitigation
(Guerra-Tamez, 2023)	Mexico	University Art Lab	Design Education	Student Engagement	User Adaptation Issues	VR	Unity VR Headsets	Creative enhancement
(Almufarreh, 2023)	Saudi Arabia	Medical University	Medical Training	Enhanced Visualization	High Costs	MR	Unity HoloLens 2(MR Headsets)	Practical training needs
(Shaghaghian et al., 2024)	USA	Engineering Course	STEM Education	Student Engagement	Technical Complexity	AR	ARKit (ios) Unity	Technical complexity
(Figueroa-Garrido et al., 2024)	Peru	Engineering Workshop	STEM Education	Enhanced Visualization	Hardware Limitations	VR	Blender VR Headsets	Cognitive visualization
(Shaghaghian et al., 2024)	USA	Engineering Course	STEM Education	Student Engagement	Technical Complexity	AR	ARKit (ios) Unity	Technical complexity
(Cross & Boag-Hodgson, 2025)	UK	Aviation Simulator	STEM Education	Collaborative Learning	High Costs	XR	Unreal Engine XR headsets	Collaboration & communication

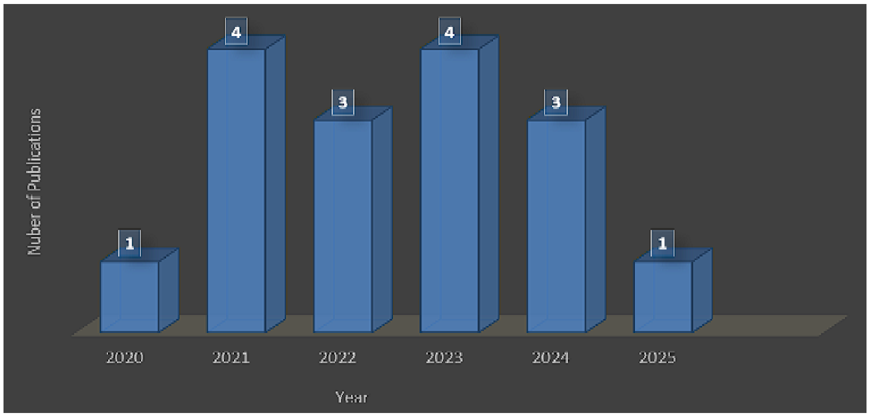

Figure 2. Publications data

Figure 2 shows the publishing trends of 16 articles on the use of spatial Computing in education from 2020 to 2025. It shows that there were 1 publication in 2020, 4 in 2021, 3 in 2022, 4 in 2023, 3 in 2024, and 1 in 2025, indicating a steady increase in research starting in 2022. This rise is likely due to technological advancements, increased research funding, and greater awareness of spatial Computing's role in enhancing educational outcomes (Al-Ansi et al., 2023).

Geographic Distribution of Research by Continent

Figure 3 shows an analysis of the 16 selected studies in this SLR across six continents utilizing spatial Computing in education. Asia leads with 6 studies, followed by the USA with 4 studies, and Europe with 4 studies. Africa accounts for 2 studies. This distribution highlights the global interest in spatial Computing, with Asia, the USA, and Europe leading the research efforts, while Africa shows limited but growing involvement.

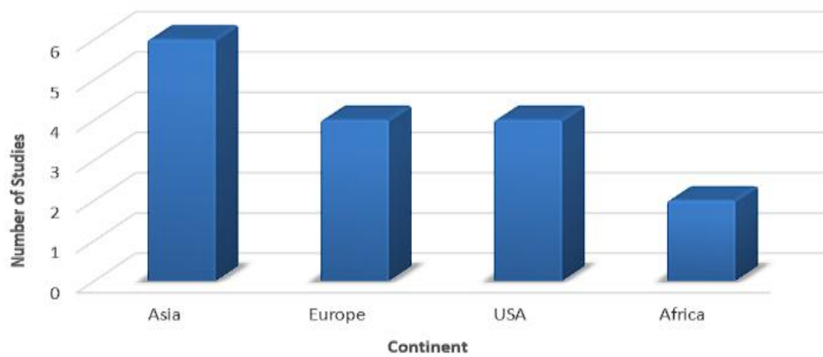

Figure 3. Geographic distribution

Factors Influencing Spatial Computing Implementation

Figure 4 summarises the key implementation factors identified across 16 studies. Collaboration and communication tools were highlighted in 4 studies. Similarly, cost-effectiveness and technical complexity emerged as prominent barriers, each reported in 4 studies. Accessibility challenges were highlighted in 3 studies, while Safety and Risk Mitigation were mentioned in 2 studies.

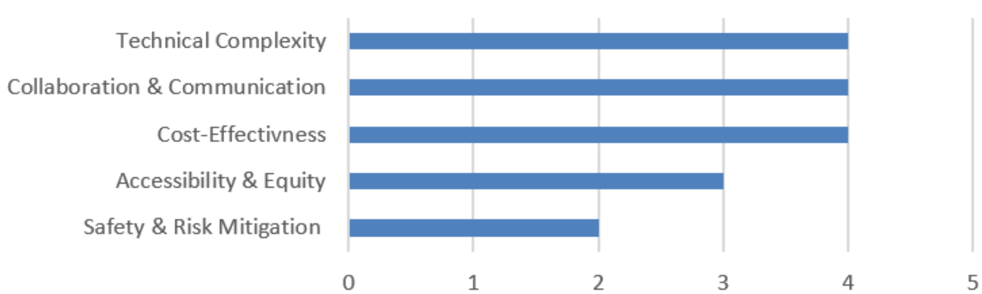

Figure 4. Factors influencing spatial computing implementation

Applications Of Spatial Computing in Education

Table 3 summarises the findings on the applications of spatial Computing in education. The studies reviewed highlight its use in architectural education (4 studies), STEM education (7 studies), design education (4 studies), and medical training (1 study).

Table 3. The application of spatial computing in education

Applications	Studies
STEM Education	7
Architectural Education	4
Design Education	4
Medical Training	1

The Benefits of Spatial Computing in Education

Table 4 outlines the key benefits identified across the studies. Enhanced visualization emerged as the most reported in 6 studies. Student engagement was strongly linked to the use of interactive tools mentioned in 5 studies, while collaborative learning was supported by multi-user environments mentioned in 3 studies. Safety also played a significant role, as mentioned in two studies.

Table 4. The benefits of spatial computing

Benefits of Spatial Computing Technologies	Number of Studies
Enhanced Visualization	6
Student Engagement	5
Collaborative Learning	3
Safety	2

Challenges Of Spatial Computing in Education

Figure 5 illustrates the frequency of key implementation challenges identified across 16 Spatial Computing educational studies. Technical complexity was mentioned by four studies, while hardware limitations emerged from six studies, followed by User adaptation issues and high costs, which were equally highlighted by three studies.

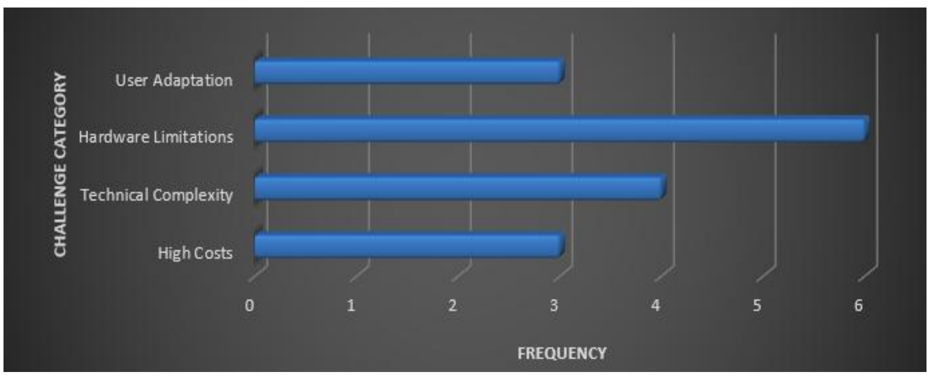

Figure 5. Challenges of spatial computing in education

Discussion

This discussion addresses the research questions in this study by utilizing the insights gained from the final 16 selected studies. Through thematic analysis, the discussion explores the core opportunities, challenges, applications, and enabling technologies of spatial Computing in educational settings.

The Application Areas of Spatial Computing in Education

STEM Education

Spatial Computing has revolutionized Science, Technology, Engineering, and Mathematics (STEM) education through three key ways.

Experiment Safety & Fear-Free Practice

Through VR, students are now able to conduct dangerous experiments in a controlled environment. For instance, Ndlovu et al. (2023) have created a VR chemistry lab for pupils using Unity and VR goggles, enablingners to perform dangerous chemistry experiments virtually without notional physical hazards and environmental contamination while still Similarly, Soliman et al. (2021) developed VR simulations in industrial mechatronics so that students could become familiar with complex machines without the risk of injury.

Enhancing Comprehension of Abstract Ideas

AR and MR have proved useful for modelling abstract content in STEM education. Shaghaghian et al. (2024) used AR overlays on smartphones using Unity to enable students to perceive spatial matrices in mathematics, bettering their conceptual comprehension. Balakrishnan et al. (2021) implemented AR head-mounted displays with ARCore in real-time mechanical-assembler training systems in engineering laboratories, fostering spatial reasoning and task effectiveness. Overall, the adoption of technologies in education, such as VR, improves the learning process and styles in delivering real-time experiences, as argued by Xulu et al. (2024); Ndlovu et al. (2025) in the adoption of GenAI tools

Technical Support and Systemic Barriers

While these benefits were evident, implementing spatial computing technologies was not without challenges. Mapfumo et al. (2024) noted that teacher training and institutional support are required for successful implementation, especially in low-resource settings. Moreover, they stressed the need to bridge the infrastructure, cost, and skill gulf to bring it into further play. Mutunhu et al. (2023) also noticed that "it is necessary to address not only accessibility features, but also inclusive design to provide equitable engagement" for students of varying abilities.

Architectural Education

Architectural education integrates Design theory, technical knowledge, structural knowledge, environmental policy, and visual representation (Hajirasouli & Banihashemi, 2022). Learners are challenged to think spatially and learn digital modelling skills when designing and representing complex forms of buildings. The field of architecture education has traditionally been based on studio-based learning and physical modelling; however, recently these traditional model-based pedagogic approaches have been complemented with digital technology to meet the new demands of architecture practice (Serrano-ausejo & Mårell-olsson, 2024).

Spatial Computing is becoming an enabling driver in this regard, providing capabilities for immersive visualization and live collaborative design (Das et al., 2022). For example, Das et al. (2022) utilized Unreal Engine and VR headsets to optimize design workflows in Danish architectural offices, promoting fast client feedback through 3D walk-throughs. Mapfumo et al. (2024) observed that despite the high perceived usefulness of such tools, effort expectancy in terms of the learning curve is still a major obstacle to usage between students and teachers.

Osorto Carrasco & Chen (2021) employed MR headsets and Revit software for interactive BIM, where the users could interact with virtual building structures in MR spaces, and experienced gesture latency as a major issue to their usability. Similarly, Urban et al. (2022) utilized VR headsets and BIM to support joint 3D model review in the Austrian construction studies.

Together, this body of work demonstrates that Spatial Computing improves accuracy and facilitates mutual engagement and communication among various stakeholders of architectural training. Nevertheless, high technical complexities, steep learning curves, and performance-related problems (e.g., gesture latency) are still proving to be substantial obstacles for its seamless integration.

Design Education

Design studies in education deal with the development of creative strategic thinking, visualization and spatial reasoning in the context of product, interior, or industrial design (Chen et al., 2024). These processes have been greatly improved with the introduction of spatial computing capabilities, allowing for both 3D modelling and real-time collaboration.

VR has turned out to be quite efficient at encouraging creative thinking and the exploration of space. Chen et al. (2024) adopted VR-based 3D modelling in Unity to attain better creativity and collaboration among students in design studios. The immersive space enabled students to see and create digital objects in real time, fostering experimentation and more robust spatial reasoning. However, Mapfumo et al. (2024) reported that long-term use of VR caused some students to feel uncomfortable due to physical strain, which showed a certain conflict between immersivity and ergonomics.

From this perspective, Augmented Reality (AR) has potential benefits from a practical viewpoint on task execution and contextual interaction. Balakrishnan et al. (2021) showed that AR glasses adjoined with Google ARCore improved chrono-efficiency in engineering design through 3D models projected on actual environments. They don't only get to interact with brand of out-of-the screen digital components in situe which makes AR especially interesting when it comes to being precise and working in a group.

Although VR is ideal for visual creativity and spatial exploration, AR is more useful for real-time tasks and context-aware task interaction. There are unique affordances for each of those technologies VR for environmental, exploratory and open-ended design processes and AR for implementation and application-driven design tasks. Which spatial computing tool to choose depends on what is to be learned and what the cognitive requirements of the design task are.

Medical Training

Key competencies, including medical decision making, procedural precision, doctor's diagnostic reasoning, and muscle memory, are taught by means of theoretical teaching, simulation, and hands-on training (Pro, 2024). Spatial computing technologies such as VR and MR have transformed this paradigm, providing safe, immersive environments in which complex medical procedures can be practiced time and time again without causing harm to patients (Javaid & Haleem, 2020).

VR simulations enable learners to practice their procedural routines and hone their psychomotor skills as they engage in repetitive, scenario-based training. For example, Cross & Boag-Hodgson (2025) demonstrated that VR micro-learning modules led to significant knowledge retention and skill acquisition, especially when students were involved in task-based learning processes iteratively. Similarly, Mapfumo et al, (2024) stated that VR tools do enable decision-making under pressure by learners who are situated in authentic emergency situations within a safely controlled environment. Although the gaming engine Unity allows us to develop these kinds of interactive simulations and serious games, the cost of implementation represents a serious limitation to their widespread use, particularly in the case of the developing world.

Meanwhile, Mixed Reality (MR) brings further value in the form of the combination of reality and digital overlay. Al-Ansi et al, (2023) pointed out that with MR systems students can orient themselves in space and learn to perform surgical procedures in correct anatomical layers with responsivity for the environment. This supports kinaesthetic teaching, which is so important for tactile-sensitive procedures.

VR and MR combined not only simulate clinical contexts but also contribute toward the development of fundamental medical skills such as decision-making and risk assessment, muscle memory and procedural fluency. There is a good alignment between including these in a component-based approach of medical teaching, allowing acquisition of skills as well as reflective learning.

Factors Influencing the Implementation of Spatial Computing in Education

Collaboration and Communication

Spatial Computing encourages collaborative learning due to the co-located virtual worlds that enable live interactive engagement(Clauss et al., 2021). Cross and Boag-Hodgson (2025) demonstrated how multi-user VR flight simulators enabled students of aviation to practice crew coordination verbally as well as gesture-led interactions, realistically simulating the actual cockpit team working. Urban et al. (2022) also discovered how AR walkthrough of BIM software allowed distributed teams to annotate and validate 3d models in a shared mode to reduce the time of design iteration compared to standard practice. Deployment of the Photon Network by Zicheng and Ao (2023) also demonstrated how synchronic teamwork in VR works, increasing the efficacy of problem-solving, albeit with detectable network delay with more than three users in parallel. Collectively, the papers demonstrate how spatial computing can extend the availability of spatial workspaces beyond geographical constraints and introduce new interface development as well as network stability challenges.

Cost Effectiveness

The financial implications of spatial computing adoption present both opportunities and barriers. While Wen et al. (2021) showed that Webxr solutions could deliver VR experiences through standard browsers at minimal cost, high-end implementations like architectural VR labs required expensive devices, plus BIM software licenses (Urban et al., 2022). Balakrishnan et al. (2021) demonstrated cost-effective AR engineering training using smartphone-based ARCore but noted limitations in tracking precision compared to dedicated AR headsets. The studies reveal a clear trade-off between accessibility and capability, with 6 of 16 studies identifying cost as the primary adoption barrier, particularly in resource-constrained institutions (Maasthi et al., 2022). Emerging solutions like cloud-based rendering and device-agnostic Webxr may help bridge this gap (Wen et al., 2021).

Technical Complexity

The implementation challenges stem from the high learning curves of the software, as well as the complex integration requirements of the system (Dube & Dube, 2023; Safikhani et al., 2022). Das et al. (2022) found that one hundred and twenty hours of training were necessary for architecture students to skilfully work using Unreal Engine for VR walkthroughs, compared to the 40 hours to master basic BIM software. Shaghaghian et al. (2024) found that the implementation of ARKit required continuous calibration of fifteen to thirty minutes per training cycle to achieve accuracy in engineering classes. These technical requirements pose a big barrier to adoption, even in cases complicated by the need to combine spatial computing software with the dominant learning management system (Almufarreh et al., 2023).

Accessibility and Equity

The spatial computing implementations must consider the diverse needs of learners and the differences in available resources. Maasthi et al. (2022) found that outdoor mixed reality applications in Indian vocational schools were regularly hindered by the intense sunlight overwhelming the HoloLens displays and by erratic power supplies. In contrast, Wen et al. (2021) illustrated how browser-based Webxr could increase accessibility for remote learners, though they noted the variable performance on diverse devices and browsers. These authors also pointed to challenges for learners with disabilities, while virtual reality created new possibilities for some, such as spatial learning opportunities for dyslexic students. It also created barriers for others, including motion sickness suffered by 38% of users, as found by (Guerra-Tamez et al.,2023). Three studies expressly called for the use of more inclusive design practices and the creation of low-cost alternatives to ensure equitable access (Balakrishnan et al.,2021; Wen et al.,2021).

Safety and Risk Mitigation

Although spatial computing eliminates physical dangers in training environments, new ethical challenges have also been introduced. Ndlovu et al. (2023) confirmed that virtual reality chemistry labs completely banish exposure to dangerous materials; yet cautioned that essential laboratory familiarity had to be retained to give users procedure familiarity. Soliman et al. (2021) underlined that while augmented reality and virtual reality simulations reduced engineering training accidents, careful planning had to be employed to avoid users acquiring dangerous habits in the virtual environment. Maguraushe (2021) notes that when adopting technologies there is a growing concern about student privacy. Almufarreh et al. (2023) highlights that MR experiences that record world settings, as well as the psychological ramifications of extended immersion, which both require study. Two works particularly called for the development of ethical principles to be established that control the application of spatial Computing in education (Almufarreh et al.,2023; Zicheng & Ao, 2023).

Benefits of Spatial Computing Technologies in Architectural Education

Enhanced Visualization

Spatial technology enables students to visually see and interact with concepts as 3d images. In medicine, Almufarreh et al. (2023) demonstrated that MR headsets enable students to examine body parts closely with tissue layers that look real. They can rotate and observe the same model from a different perspective, something that's easier to comprehend compared to 2D textbook images. Architectural education also benefited from VR walkthroughs. Das et al. (2022) ascertained that the image generated using Unreal Engine enabled students to visualize parts fitting into each other and identify design errors better compared to standard blueprints. STEM disciplines employed the same, such as Figueroa-Garrido et al. (2024), VR engineering simulations, to teach concepts in structural mechanics using interactive 3d images.

Student Engagement

Immersive technology makes students more engaged and interested in various learning environments. Chen et al. (2024) discovered that students in grade school using Tilt Brush in VR were more engaged in learning compared to their peers in standard art classes because the new technology promoted creativity and exploration. University students, as Guerra-Tamez et al. (2023) discovered and spent more time working on tasks of digital sculpting utilizing VR tools compared to standard software. They declared the interactive process more enjoyable. The advantages of engagement also exist in technical fields. Balakrishnan et al. (2021) discovered that engineering students wished to rehearse using

AR assembly simulations for a longer duration, with more students stating that they found the experience to be more appealing compared to learning from textbooks. Six studies attributed the increased engagement to the new experience of spatial computation and its capability to give instant, interactive responses.

Collaborative Learning

These technologies enable individuals to collaborate and converse immediately in various locations (Sebiraj et al., 2024; Urban et al., 2022).BIM and AR headsets were employed to enable architecture students to collaborate and provide instant feedback on 3d designs (Cross & Boag-Hodgson, 2025). Unreal Engine and Extended Reality headsets were employed in XR to implement a team environment so trainees can exercise team performance in the cockpit (Cross & Boag-Hodgson, 2025).A VR system based on Photon Network was developed to enable individuals to collaborate in industrial design in real time, but issues of syncing existed (Zicheng & Ao, 2023).

Safety

Spatial Computing makes it safe to practice hazardous or sensitive tasks. Ndlovu et al. (2023) eliminated chemical hazards in chemistry lessons with VR laboratories in which students were able to combine hazardous chemicals and observe reactions free from worry about their safety. Soliman et al. (2021) developed AR/VR training simulations for engineering students to handle heavy equipment and electrical controls, reducing training mishaps compared to training in the actual equipment. In medical training, MR surgical training simulations permitted the same life-critical operations to be practised numerous times without harming patients(Almufarreh et al., 2023).

Spatial Computing Technologies and Tools for Education

Virtual Reality (VR)

Virtual Reality (VR) creates fully immersive digital environments that transform how students interact with complex concepts, with studies demonstrating its effectiveness across various disciplines. Ndlovu et al. (2023) developed a VR chemistry lab using Unity, Blender software and VR headsets, enabling safe experimentation while improving practical skills, while Chen et al. (2024) combined Blender's 3d modelling capabilities with Unreal Engine to create interactive design studios that boosted elementary students' spatial reasoning. The core technologies driving VR adoption include development platforms like Blender, Unity, and Unreal Engine for building interactive simulations, VR headsets such as Oculus Rift and HTC Vive for full immersion, and 3d modelling tools like Blender for asset creation (Chen et al., 2024).

Augmented Reality (AR)

Augmented reality (AR) enhances actual learning environments by superimposing digital information into the real world, benefiting STEM and professional and technical education immensely (AlGerafi et al., 2023). Balakrishnan et al. (2021) demonstrated the effectiveness of AR in teaching engineering by utilizing Google ARCore and AR Headsets to display machine parts to actual machines, reducing students' assembly errors. Shaghaghian et al. (2024) employed Apple's ARKit and motion sensing to teach spatial matrices, resulting in improved test scores. Key AR technology comprises mobile application software such as ARKit and ARCore, easily accessed by smartphones, development software such as Unity AR Foundation and specialized software such as Vuforia for the ability to identify (Soliman et al., 2021).

Mixed Reality (MR)

Mixed reality (MR) blends the virtual world and the real world to produce interactive learning environments, particularly for technical classes (Kıdık & Asiliskender, 2024). Almufarreh et al. (2023) employed the use of Microsoft's HoloLens 2 MR headsets and Unity's MRTK toolkit to develop MR training in surgery, enabling medical students to practice and master their skills. In another case, Osorto Carrasco & Chen, (2021) integrated Autodesk's Revit BIM models with MR systems, enabling users to utilize gestures to minimize design errors in architecture. The construction of mixed reality systems requires special hardware, such as MR Headsets like HoloLens 2 and Magic Leap 1 , Elsamahy et al. (2020), for spatial computation, development software such as Unity MRTK , Maasthi et al. (2022), and special software such as Revit for architecture visualization (Urban et al., 2022).

Extended Reality (XR)

Extended reality (XR) integrates VR, AR, and MR technologies into practical teaching tools for various subjects. Guerra-Tamez et al. (2023) developed cross-platform XR art studios with Webxr, allowing more students to participate since they can use a web browser. Cross & Boag-Hodgson (2025) developed entire XR flight simulators with Unreal Engine that can be used for training. Implementing XR technology involves web-based environments such as Webxr to utilize on any equipment, network tools such as Photon Engine for working in a team and hybrid devices that can utilize both VR (Oculus) and AR (HoloLens) in tandem (Alnagrat et al., 2022).

Challenges of Spatial Computing Technologies in Architectural Education

High Implementation Costs

The cost of spatial computing tools remains a significant challenge for adoption. Urban et al. (2022) noted that mixed reality devices, such as MR headsets, are not a viable option for many institutions because the hardware alone costs thousands of dollars. Similarly, Cross and Boag-Hodgson, (2025) noted that true-to-life VR environments generate costs in hardware, software, and ongoing maintenance. Almufarreh et al. (2023) termed MR-based medical training programs, which use Mixed Reality headsets and Unity, as incredibly cost-prohibitive to budgets in underfunded regions(Maqsoom et al., 2023).

Technical Complexity and Learning Curve

The high technical demands of spatial computing tools impede seamless integration. Das et al. (2022) found that architectural workflows based on Unreal Engine require advanced programming skills, resulting in a steep learning curve for students and teachers. Shaghaghian et al. (2024) detailed challenges in calibrating Google ARCore and hand-tracking sensors for engineering education, suitable for a technical background. Osorto Carrasco and Chen (2021) experienced latency issues when attempting to deploy the HoloLens 2 (MR headsets) gesture recognition function in a BIM training activity, when trying to integrate mixed reality tools.

Hardware Limitations

Hardware Device limitations impede the capability of spatial computing applications. Balakrishnan et al. (2021) described that the limitations of AR headsets' field of view (FOV) reduced immersion during AR-based mechanical assembly tasks. Figueroa-Garrido et al. (2024) mentioned that Unity and Blender both require high-end GPUS to render complex 3d structures, which many institutions do not possess. Elsamahy et al. (2020) described criticism of some MR headsets like Magic Leap 1, for short battery life and overheating during prolonged use in design mixed reality sessions.

User Adaptation Challenges

Users continue to encounter physiological and cognitive adaptation barriers. Chen et al. (2024) found that elementary students experienced motion sickness while wearing the VR headsets during 3d modelling and thus could endure a session for a limited amount of time. Guerra-Tamez et al. (2023) noted discomfort from prolonged use of the virtual reality headsets in art classes. The absence of tactile feedback in the VR chemistry lab environments created using Unity discouraged a feeling of realism for the learners (Ndlovu et al., 2023).

Theoretical Implications

Integration of spatial Computing (XR, VR, MR, AR) into schooling has profound theoretical resonance, redefining pedagogy at its essence in bridging the gap between abstract principles and experiential knowing. These technologies, such as Microsoft HoloLens for 3d visualizations or Unity for interactive modelling, facilitate active, student-driven learning, encouraging superior intellectual engagement with spatial reasoning in STEM, architectural, as well as vocational studies. The theoretical foundations of this transformation are further illuminated by Mapfumo et al. (2024), who applied the Technology Acceptance Model (TAM) to explain how perceived usefulness and ease of use significantly influence educators' willingness to adopt spatial computing technologies. Their adoption demands rethinking institutional infrastructures in filling out the gap in terms of affordability as well as technical intrusion (e.g., Unreal Engine workflows), demanding that policymakers ensure funding support for affordable tools such as Webxr as well as standardized content repositories. Their transformative power as collaborative platforming ensures the need for multi-stakeholder partnerships in implementing IT support structures as well as educational programs empowering teachers to implement immersive means in their most beneficial applications. Ethically, spatial Computing demands universal principles for designing in terms of inclusiveness (e.g., ARCore for diverse learners) as well as controls for minimizing physical distress. From the theoretical point of view, this foretells movement towards hybrid learning environments in which spatial Computing not only deepens learning as well as mastery but advances conventional curriculums toward integrating adaptive, moral, as well as internationally accessible, immersive experience, yielding a platform for future research on AI-driven adaptive learning as well as long-term effectiveness across the curriculum (see Figure 6).

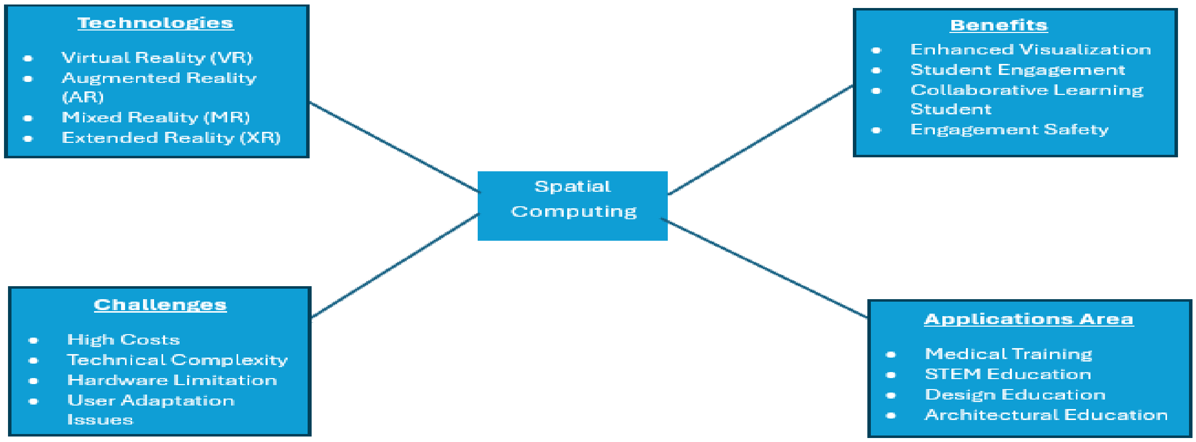

Figure 6. The spatial computing conceptual framework

Limitations of the Study

There are several limitations of this systematic literature review that may influence the validity and generalizability of its findings. Firstly, studying only those studies published between 2020 and 2025 in English ignores foundational research from prior years and non-English contexts, limiting historical and global perspectives (Guo et al., 2021). On the second account, the geographical imbalance where more than sixty percent of studies were conducted in Asia, Europe, and the USA raises the issue of pushing findings towards high-resource settings, which appears to reduce their pertinence in low- and middle-income parts of the world (Al-Ansi et al.,2023; Ndlovu et al.,2023). This gap is particularly evident when compared to recent work by Mapfumo et al. (2024), which specifically examines adoption challenges in African educational contexts, highlighting unique barriers such as infrastructure limitations and lack of technical support that are underrepresented in our current dataset. Third, the review showed a narrow disciplinary focus of 16 studies, prioritizing architectural education, STEM, and design fields, with clear application gaps toward humanities or primary education (Soliman et al.,2021). Although catalogued, scalability issues, infrastructure costs, GPU requirements, and long-term maintenance were not thoroughly vetted, but are of utmost importance to real-world adoption. Furthermore, the exclusion of grey literature (e.g., technical reports, case studies) may have resulted in missing pragmatic insights into implementation barriers. Flexibility in methodology utilization, readership, and focus may have been too rigid, eventually excluding studies utilizing different nomenclature frameworks, e.g., "XR Pedagogy." While difficulties in user adaptation were highlighted (e.g., motion sickness, discomfort induced by use of the device), this was neither consistent nor systematic and resulted in gaps in mitigation strategies, which fell under the pedagogical umbrella. Finally, since the paper relies solely on peer-reviewed empirical studies retrieved from databases (i.e., IEEE Xplore), it may be subject to bias in publication (i.e., publication bias) whereby positive outcomes are published over negative or null results. These limitations highlight the importance of future studies to take on broader temporal, linguistic, and geographical scopes combined with mixed-method analyses around scalability, accessibility, and learner adaptability (Elsamahy et al., 2020).

Future Research

Future work must follow three separate directions to expand the scope of learning through leveraging spatial Computing. First, there is a need to create low-cost alternatives, e.g., WebXR and cloud-based systems, to break the conventional barriers of cost and technical complexity. Without such solutions, spatial Computing will remain beyond the reach of under-resourced institutions, and its findings generalizable perhaps only to high-income educational settings. Second, extensive explorations should be made to determine the performance of learning in a range of fields using existing research in architectural and STEM education, to overcome the limitations of traditional approaches in primary education and human sciences. Failure to generalize application areas may bias the relevance of the review towards technically based disciplines and thereby make it less relevant to broader pedagogical contexts. Third, standard testbed platforms must include the existing adoption models, such as TAM and UTAUT, as well as instructional performance metrics, to assess both technological adoption and instructional performance. In the absence of standardized assessment systems, synaptic studies are piecemeal in their comparisons, thereby reducing the credibility and cumulative strength of our evidence base.

New directions also open up with the application of AI-based personalization and combined physical-digital spaces, especially in collaborative environments. As these directions are explored, scholars must continue to adhere to inclusive design considerations that enable accessible access to diverse institutional settings.

Conclusion

This SLR explored how spatial Computing enhances architectural and design education by improving spatial reasoning, visual engagement, procedural safety, and collaborative learning. It also identified increased learner motivation and task performance across STEM and medical training contexts. These technologies help in visualization, participation, and collaboration, thus adding valuable benefits in learning. Nevertheless, there are challenges such as cost, complexity, and hardware limitations. Recent work provides additional insights into these challenges, categorizing them into technological, teacher-based, and learner-based barriers, and suggesting that adoption frameworks like TAM and UTAUT could help address these issues systematically. Breaking through those hurdles will be important to being able to fully utilize the learning benefits of spatial Computing. The hardware must be made affordable, and spatial Computing should be integrated into the curriculum; we will need future research to solve these issues. It illustrates potential lessons from best practice if the comparison of spatial Computing to traditional learning can be made. Research is necessary to establish spatial Computing along with the Internet of Things and Artificial Intelligence, so that the training can be as to the person. For example, Xiong et al. As an example, one study demonstrated that learners are more engaged when augmented reality is delivered using Microsoft HoloLens and Unity, whereas another proposed use of XR to gain insights into immersive design and design. Moreover, this can now be intermixed with spatial Computing and other related smart devices, like Leap Motion and Google ARCore, to offer real-time feedback of your entire experience and offer you interactive learning. The establishment of predictive models to predict the behaviour of learners can also ensure maximum personalization to improve their performance level.

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