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Υπογραφή:

Σχετικά με εμένα

Ευχαριστίες

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Με εκτίμηση,

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Περίληψη

Η παρούσα μελέτη εμβαθύνει στην επίδραση του ψηφιακού μετασχηματισμού στην εκπαίδευση, με ειδική έμφαση την ενσωμάτωση της Επαυξημένης Πραγματικότητας (AR) ως τεχνολογική τάση. Οι δυνατότητες της AR για την εμπλοκή των μαθητών και τη βελτίωση των εκπαιδευτικών εμπειριών διερευνώνται από διάφορες οπτικές γωνίες, υπογραμμίζοντας το ρόλο της στο μετασχηματισμό των μεθόδων διδασκαλίας και μάθησης. Παρέχοντας μια λεπτομερή ιστορική αναδρομή και οριοθετώντας τις διαφορές μεταξύ AR, Εικονικής Πραγματικότητας (VR) και Μικτής Πραγματικότητας (MR), η μελέτη αυτή δημιουργεί μια θεμελιώδη κατανόηση της επίδρασης της AR στην εκπαίδευση. Παρουσιάζει μια διεξοδική ανάλυση των κατηγοριών AR, συμπεριλαμβανομένων των βασισμένων στο υλικό, στο λογισμικό και στις εφαρμογές, προσφέροντας πληροφορίες για ποικίλες εφαρμογές AR, όπως η βιομηχανική, η υγειονομική περίθαλψη, η εκπαίδευση και η ψυχαγωγία. Η έρευνα αυτή εξετάζει επίσης διάφορα λογισμικά ανάπτυξης AR, παρέχοντας έναν ολοκληρωμένο πίνακα σύγκρισης για την ανάπτυξη εφαρμογών στην AR. Στο πλαίσιο της εκπαίδευσης, η μελέτη υπογραμμίζει τη σημασία της AR σε περιβάλλοντα τάξης, συζητώντας τα οφέλη, τις προκλήσεις και τις πιθανές παγίδες της. Παρουσιάζει πρακτικές περιπτώσεις χρήσης της AR σε διάφορα εκπαιδευτικά πλαίσια, όπως η Επιστήμη, η Τεχνολογία, η Μηχανική και τα Μαθηματικά (STEM), οι τέχνες και οι ανθρωπιστικές επιστήμες, η εκμάθηση γλωσσών και τέλος η ειδική εκπαίδευση. Η εργασία περιλαμβάνει παραδείγματα επιτυχημένων εφαρμογών AR και προσφέρει καινοτόμες στρατηγικές εφαρμογής AR κατά την εποχή του υβριδικού μοντέλου και του ψηφιακού μετασχηματισμού. Καταλήγει με μελλοντικές ερευνητικές κατευθύνσεις, υπογραμμίζοντας τις αναδυόμενες τάσεις στην AR και την Εκπαίδευση, τον ρόλο της Τεχνητής Νοημοσύνης (AI) και της Μηχανικής Μάθησης (ML) στην ενίσχυση των εμπειριών AR, καθώς και την ανάγκη για πρόσθετες πρακτικές μελέτες για την υιοθέτηση της AR σε εκπαιδευτικά ιδρύματα και σχολεία.

Abstract

This study delves into the impact of digital transformation in education, with a specific focus on the integration of Augmented Reality (AR). AR's potential for engaging learners and enhancing educational experiences is explored from various angles, underlining its role in the transformation of teaching and learning methods. By providing a detailed history and demarcating the differences between AR, Virtual Reality (VR), and Mixed Reality (MR), this study creates a foundational understanding of AR. It presents a thorough analysis of AR categories, including hardware-based, software-based, and application-based, offering insights into diverse AR applications like Industrial, Healthcare, Education, and Entertainment. This research also examines various AR development software, providing a comprehensive comparison table for the AR development. In the context of education, the study emphasizes the significance of AR in classroom settings, discussing its benefits, challenges, and potential pitfalls. It presents practical use cases of AR in diverse educational contexts, such as STEM, Arts and Humanities, language learning, and special education. The work includes successful AR application examples and offers innovative AR implementation strategies for the digital transformation and hybrid model era. It concludes with future research directions, underlining emerging trends in AR and Education, the role of Artificial Intelligence (AI) and Machine Learning (ML) in enhancing AR experiences, and the need for additional practical studies for AR adoption in educational institutions and schools.

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Acronyms

AI	Artificial Intelligence	**AR**	Augmented Reality
DT	Digital Transformation	**IT**	Information Technology
ML	Machine Learning	**MR**	Mixed Reality
MRTK	Microsoft Mixed Reality Toolkit	**OST**	Optical See-Through
RQ	Research Question	**STEM**	Science, Technology, Engineering, and Mathematics
VR	Virtual Reality	**VST**	Video See-Through


AR EVERYWHERE
FROM PRIMARY SCHOOL TO HIGHER EDUCATION
2023 | EDITED BY
GEORGIOS K. ROUSSOS

Preface

As we stand at the cusp of a new era, the world is about to embrace a fascinating revolution - where reality is amplified, and our perceptions are enriched by the power of technology. The phrase "AR Everywhere" isn't a distant dream; it's an imminent reality, echoing the earlier mantra of "AI Everywhere," which has already begun transforming our world in unprecedented ways. This invisible revolution of Augmented Reality (AR) is silently weaving its way into our daily routines, promising to reshape the contours of our experiences, perceptions, and interactions with the world around us.

Just as Artificial Intelligence (AI) has permeated every facet of our lives in 2023 - from our smartphones to our cars, shopping experiences to our workplaces - AR is on the brink of a similar ubiquitous presence. And just as we've witnessed the transformative power of AI, we're set to see AR unfurl its wings, expanding the horizons of our realities. AR holds the potential to revolutionize industries, reshape education, and redefine entertainment - embedding itself in every corner of our existence.

This thesis, "Digital Transformation in Education: Enhance Learning by Adopting Augmented Reality in Classroom," aims to explore the significant role AR can play in the educational landscape. The adoption of AR in classrooms is a testament to the digital transformation that is sweeping across education, enhancing learning experiences, fostering engagement, and transforming pedagogical approaches.

As we start this journey to learn more about the changing role of augmented reality in digital transformation and how it affects education, we'll be entering a world where reality isn't just what we see, but a rich, interactive experience that teaches, engages, and fascinates. Let's step into this exciting new era of technology and see how augmented reality will bring about a revolution and make the phrase "AR Everywhere" a way of life.

1
INTRODUCTION

This work examines the role of digital transformation in education, particularly emphasizing the use of Augmented Reality as a tool to improve the learning experience. As current technologies continue to develop and infiltrate different facets of daily life, the education industry provides several chances for change and innovation. One such potential is the use of augmented reality technology, which may facilitate interactive, immersive, and engaging learning experiences.

As part of the wave of digital transformation, augmented reality enables the superimposition of digital information on the actual environment, bridging the gap between theoretical understanding and practical application. This paper will investigate how augmented reality may be implemented in educational contexts, exploring its benefits and potential obstacles and describing successful implementations.

1.1 Structure of the Thesis

Digital technologies are ushering in a new era of educational transformation. This thesis mainly focuses on the role of Augmented Reality in shaping the future of learning. It is organized in a manner that provides a comprehensive exploration of digital transformation in education and the adoption of AR technologies. Below is a revised and enhanced summary of each chapter:

Chapter 1, Introduction: The initial chapter introduces the reader to the broad subject of the research, setting the stage for the in-depth discussions that will follow. It familiarizes the reader with the research context and outlines the research objectives.

Chapter 2, Digital Transformation in Education: This chapter takes a deep dive into the profound impact of digital transformation on the world of education. It examines how various aspects of this phenomenon are revolutionizing teaching methods, curriculum delivery, learner engagement, and administrative procedures in the educational sector.

Chapter 3, Introduction to Augmented Reality: This chapter delves into an in-depth exploration of Augmented Reality (AR), tracing its origins and evolution, and its various applications across diverse fields. It starts by providing a historical context, exploring the key milestones and technological advancements in AR. The section proceeds to elucidate the differences between AR, Virtual Reality (VR), and Mixed Reality (MR), offering a comprehensive understanding of these immersive technologies. Various categories of AR are explained, with distinctions made based on hardware, software, and application-based characteristics. The chapter also delves into AR development software, offering insights into popular platforms like ARCore, ARKit, Vuforia, and others. A comparison table further aids in understanding the relative strengths and suitability of these platforms for different AR development tasks. This section thus serves as a thorough primer on AR, laying a robust foundation for the subsequent discussion on its applications in education.

Chapter 4, This section explores the integration of Augmented Reality (AR) into education, focusing on its capability to enhance the learning experience in the digital era. The research delves into the benefits of adopting AR in classrooms, such as its potential to engage students and make learning more immersive. It underlines the importance and ultimate goal of AR adoption in classrooms, acknowledging both the benefits and potential pitfalls, including technological, pedagogical, ethical, and accessibility challenges. Various AR use cases in different subjects such as STEM, arts and humanities, language learning, and special education are presented. Furthermore, successful AR applications in various educational settings, ranging from primary to higher education, are discussed. The study also provides an in-depth analysis of tested AR Android-based applications for education and presents innovative AR implementation strategies in the classroom for the digital transformation era. Lastly, it identifies several barriers to AR adoption in education, including technical limitations, cost and accessibility issues, resistance to change, and privacy and data security concerns.

Chapter 5, Conclusions: This chapter provides the concluding remarks on the exploration of Augmented Reality (AR) in education, summarizing the key insights derived from the study. Findings underline that AR overlays digital content onto real-world contexts, offering an immersive learning environment. Various educational AR tools and applications were explored, each offering unique features such as interactive simulations and 3D visualizations. Evidence showcased AR's potential to enhance student engagement and knowledge retention across various educational contexts. Conversion of traditional classrooms to AR-infused digital ones demands infrastructure considerations including internet connectivity and device availability. Two implementation scenarios were presented to guide the practical integration of AR in daily teaching. Despite technical, cost, and adoption challenges, AR holds transformative potential for education, providing immersive learning and preparing students for a rapidly digitizing world.

Chapter 6, Future Research: ed Reality (AR) in education. This includes an exploration of emerging trends in AR and Education, highlighting the potential for further development and broader adoption. It also considers the role of Artificial Intelligence (AI) and Machine Learning (ML) in improving AR experiences, noting the increased sophistication and personalization these technologies can bring to AR applications. Lastly, the section advocates for additional practical studies for AR adoption in educational institutions, emphasizing the need for more empirical evidence to inform best practices and strategies for successful integration. This ongoing research will continue to shape the landscape of AR in education, contributing to our understanding of its potential benefits and challenges.

1.2 Purpose – Scope

The scope of this work covers various aspects of AR in education, including but not limited to:

- Understanding the core concepts and technology needs of augmented reality (AR) as well as how it connects to learning theories and pedagogical techniques is the theoretical foundation.
- Reviewing the available augmented reality development tools, platforms, and educational resources.

- Application Areas: Identifying several educational fields and disciplines where augmented reality might be advantageous, ranging from science and mathematics to the humanities and the arts.
- Case Studies: Examining real-world implementations of augmented reality in the classroom, examining their successes, failures, and lessons learned.
- Examining the impact of augmented reality on learning outcomes, student engagement, and motivation.
- Potential Obstacles and Answers: Discussing the viable barriers to the adoption of augmented reality in education, such as technological challenges, accessibility, and prices, and providing potential solutions.
- Future Prospects: A discussion on the future of augmented reality in education, taking into account technological advances and developing pedagogical strategies.

This effort is to give educators and why not to students with significant insights on the potential of augmented reality as part of the digital transformation in education, therefore contributing to the development of more effective, engaging, and creative learning experiences.

1.3 Research methodology and research questions (RQs)

The research methodology employed in this thesis emphasizes the rigorous collection and examination of information sources related to Augmented Reality trends in the field of education and learning. This academic inquiry is built upon an extensive research effort that spanned an intensive period of eighteen months.

The research approach entailed a methodical and exhaustive review of scholarly literature derived from a broad spectrum of prestigious and reputable academic databases. These resources encompass Google Scholar, ResearchGate, IEEE Xplore, ACM Digital Library, Springer Link, JSTOR, ScienceDirect, Wiley Online Library, Taylor & Francis Online, and the ProQuest Research Library. The wealth of academic information extracted from these databases, including scholarly articles, journals, and research papers, contributed significantly to the comprehensive exploration and analysis inherent in this study.

As part of the research methodology, established clear criteria for including and excluding source materials. These criteria served as a guideline to filter and select the most relevant and suitable studies that align with the research objectives, thus ensuring a focused and rigorous review. The following table (Table 1) elucidates the specific parameters adopted in this thesis for the inclusion and exclusion of literature, thereby offering transparency and structure to the literature review process.

Research Criteria	**Inclusion**	**Exclusion**
Topic	Studies focusing on AR in education and learning, Digital Transformation, Smart Education, and Mixed Reality.	Studies not focusing on AR, or those focusing on AR in non-educational contexts.
Source	Research derived from academic databases, including Google Scholar, ResearchGate, IEEE Xplore, ACM Digital Library, Springer Link, JSTOR, ScienceDirect, Wiley Online Library, Taylor & Francis Online, and ProQuest Research Library.	Research derived from non-academic sources or databases not mentioned in the inclusion criteria.
Language	Studies published in English.	Studies published in languages other than English.
Type of Publication	Peer-reviewed journal articles, conference papers, research papers, scholarly articles, material from official web portals with academic sources.	Non-peer-reviewed articles, opinion pieces, blog posts, and articles from non-academic sources.
Date of Publication	Studies published within period 2010-2023 to ensure relevance and recency[1].	Studies published more than 13 years ago.
Relevance to Search Terms	Studies directly addressing or investigating the predetermined search terms.	Studies not related or only tangentially related to the predetermined search terms.

Table 1 - Research Criteria, Inclusion, Exclusion

[1] Except [40]

To optimize the literature search and ensure a wide coverage of relevant materials, a strategic combination of search terms was employed. These terms, which encapsulate key areas of focus in the study, include but are not limited to:

- Augmented Reality in Education
- AR Learning and Teaching
- AR Learning Materials
- AR Experiences
- AR Infrastructure and Classrooms
- Teacher and Student Interactions with AR
- AR in Primary, Secondary, and Higher Education
- Impact of AR
- AR Case Studies and Applications
- AR Mobile Applications
- Implementation of AR
- Mixed Reality
- Smart Education
- Digital Transformation and its Role in Education

The careful selection of these search terms aimed to encompass the most critical aspects of AR application in education and its alignment with broader digital transformation trends, thus providing a comprehensive foundation for this study.

The research questions outlined in this study are designed to provide a structured exploration into the broad field of digital transformation in education, with a particular emphasis on the integration and impact of Augmented Reality (AR). These questions lay the groundwork for the thesis, serving as a guiding beacon for the extensive research undertaken.

RQ1: How does digital transformation shape today's education and what are its main elements?

RQ2: How do AR's unique properties, advantages, and limitations differ from VR and MR, and how do they affect technology choice in education?

RQ3: What AR tools and applications are there for education, and what are their primary characteristics and requirements?

RQ4: How does AR improve classroom learning, what successful examples exist, and how can AR be effectively implemented and adopted in different educational settings?

RQ5: What changes are needed to make a traditional classroom into AR-enabled digital classroom, considering infrastructure?

RQ6: What are the main challenges and possible solutions for incorporating AR into classrooms, especially concerning technical, cost, and user adoption issues?

These questions will help shape the rest of the analysis, which will show how AR can change education in many different ways.

1.4 Terms and Definitions

In a thesis, it is essential to define "Terms and Definitions" to guarantee that the study topic is understood by everybody. It promotes clarity, prevents misinterpretation, and develops a common language between the author and readers, so boosting the readability and comprehension of the study.

1.4.1 Digital Transformation (DT)

The term "digital transformation" (DT) refers to the incorporation of digital technologies into all facets of a company or organization, which results in fundamental shifts in the company's operations, processes, and the way people interact with the company or organization [1]. It entails making use of modern technologies, such as cloud computing, big data analytics, and the Internet of Things (IoT), in order to improve efficiency, competitiveness, and innovation.

1.4.2 Augmented Reality (AR)

AR is a technique that allows the virtual incorporation of digital objects into the physical world. It is sometimes referred to as mixed reality, as it augments reality by superimposing virtual pictures on top of a physical object [2]. In other words, AR brings instructional information to life by allowing users to view and interact with attractive 3D models, resulting in enhanced engagement, understanding, and, eventually, knowledge retention. In simple words AR creates a bridge between the digital and physical world.

1.4.3 Virtual Reality (VR)

Virtual Reality, represents a digital simulation crafted by computers, which fully engages users within a constructed reality, thereby isolating them from their real, physical surroundings [3]. Users typically interact with the virtual world through devices such as head-mounted displays (HMDs), gloves, or controllers, allowing them to see, hear, and even touch the digital environment.

1.4.4 Mixed Reality (MR)

Mixed Reality (MR), also known as hybrid reality, is a technology that combines the real and virtual worlds to provide new landscapes and representations in which actual and digital items coexist and interact in real time. It allows users to engage with both physical and virtual components in the same environment, spanning the continuum from the actual world to a fully immersive virtual reality. When we say "from real to virtual" in the context of Mixed Reality (MR), we are referring to the spectrum of experiences that blend the physical and digital worlds.

At one end of this spectrum is the real environment, where interactions occur solely with physical objects. As we move along the spectrum towards the virtual end, we encounter Augmented Reality, which overlays digital information onto the physical world. Further along the spectrum, we find Augmented Virtuality, a less common term that refers to predominantly virtual spaces where real-world objects or people are dynamically integrated into and can interact with the virtual world in real-time. Finally, at the far end of the spectrum is Virtual Reality, where the user is fully immersed in a completely digital environment, with no elements of the physical world included. So, the phrase "from real to virtual" encapsulates this whole range of mixed reality experiences, from purely physical to entirely digital, with various degrees of blending in between [4]. Figure 1 can help us understand each term and its scope across the spectrum (from real to virtual)[2].

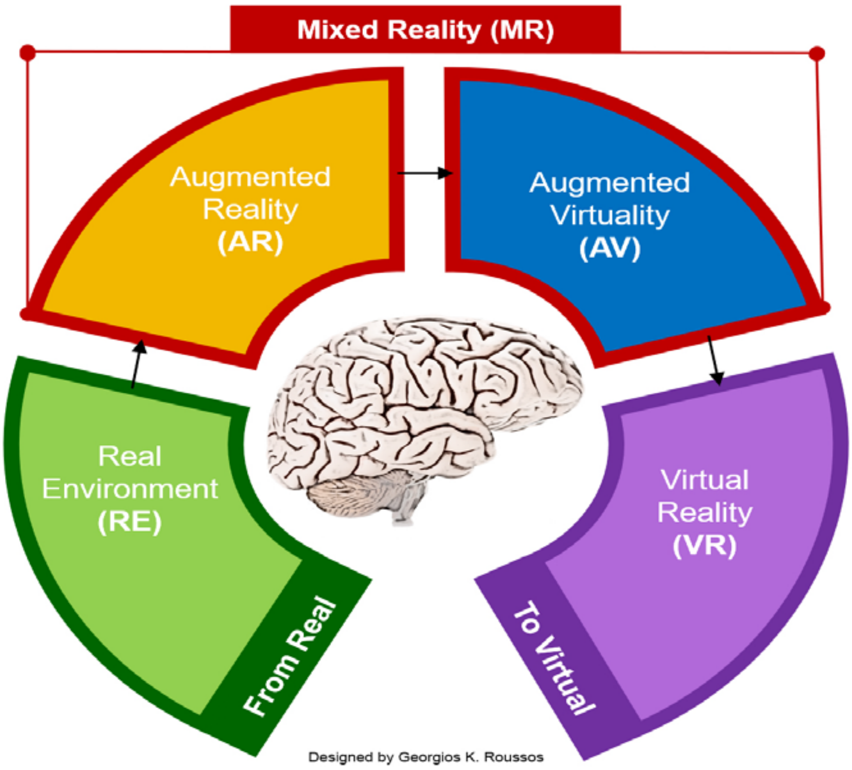

Figure 1 - From real to virtual

On the other hand, the phrase "from virtual to real" could be interpreted as moving from entirely virtual environments to ones that incorporate physical world elements. This would be a reversal of the "from real to virtual" spectrum, starting with Virtual Reality (VR) at one end—where users are fully immersed in a digital environment—and moving through Augmented Virtuality (AV) and Augmented Reality (AR) towards the real environment. However, it's important to note that in most discussions about Mixed Reality (MR), the spectrum is typically described as moving "from real to virtual." This is due to the progression of these technologies and their applications, which have historically begun with real-world interactions and evolved to incorporate increasingly sophisticated digital components.

[2] The figure1 representing the spectrum from "real environment to virtual" offers a pioneering visualization of how various mixed reality experiences are processed by the human brain. This is the first improved instance where such a comprehensive model has been developed to illustrate our perception of this continuum.

2

DIGITAL TRANSFORMATION IN EDUCATION

The advent of the digital era has fundamentally changed the way we approach learning and education. With the digital transformation revolutionizing various sectors, education has not remained untouched. Digital transformation is creating a smarter learning experience by leveraging modern technologies such as artificial intelligence, big data, and augmented reality. It's about transitioning from traditional, often rigid educational models to flexible, learner-centric systems driven by innovative digital tools.

The above paragraph underscores the fundamental shift that digital transformation has brought to the field of education. According the above information, consider the following statistics:

Digital technologies have indeed reshaped the educational landscape. According to a report by Google (2023), schools are incorporating emerging technologies, such as Artificial Intelligence, Virtual Reality, and Augmented Reality, into the classroom 82% of US teachers think using technology better prepares students for future careers [9].

Additionally, according to the Education Technology Use in Schools report that reflects the views of students, teachers, principals and district administrators on digital learning tools, states that 65% of teachers say they use digital learning tools to teach every day and 81% of teachers, see great value in using digital learning tools now and in the future [4].

Similarly, a survey conducted by Microsoft (2020) revealed that over 150,000 educators across 27 countries agree that Artificial Intelligence will play a vital role in transforming education over the next three years [10]. Furthermore, the global market for Big Data in the education sector is expected to grow at a CAGR of around 12% from 2020 to 2025, according to a report by Mordor Intelligence (2020) [11]. This trend is complemented by the rise of Augmented Reality (AR) in education, projected to grow at a CAGR of 17.93% during 2021-2026 as reported by Research and Markets (2021) [12].

Last but least, according to the Digital Education Action Plan (2021-2027) that released by the European Commission, serves as a framework to help EU Member States harness the potential of digital technologies to transform their education and training systems. The plan focuses on two strategic priorities: a) Fostering the development of a high-performing digital education ecosystem and b) Enhancing digital skills and competencies for the digital transformation. [13,14] In fostering a high-performing digital education ecosystem, the action plan suggests investment in connectivity, infrastructure, and digital equipment, alongside digital capacity building for education and training staff [13].

This digital transformation is indeed enabling a transition from traditional educational models to more flexible, learner-centric systems supported by innovative digital tools."

2.1 Primary ways to digital transformation

One of the primary ways digital transformations enhances learning is through personalized education. Traditional "one size fits all" models are giving way to individualized learning paths tailored to each student's abilities, learning styles, and interests. Advanced learning analytics allows educators to track each learner's progress in real-time, offering immediate feedback and adapting learning materials to suit their evolving needs. This personalized approach helps keep students engaged, motivated, and on track for success.

Moreover, digital transformation also drives collaboration and fosters a more interactive learning environment. With tools such as cloud-based collaboration platforms, students can work together on projects regardless of geographical location. Augmented reality and virtual reality technologies provide immersive experiences that enrich understanding and bring learning materials to life. These tools are not only making learning more interactive but also more engaging and fun.

The digital transformation is broadening access to education too. With online learning platforms, massive open online courses (MOOCs), and digital libraries, quality education is no longer confined to traditional classrooms or limited by geographical boundaries. Today, anyone with internet access can benefit from world-class educational resources, making lifelong learning a reality for many. Thus, in the digital era, digital transformation is paving the way for a smarter, more personalized, interactive, and accessible learning experience.

This study aims to illuminate the transformative impact of digital advancements on educational practices, specifically focusing on enhancing the learning experience through integrating Augmented Reality in classroom environments. Through exploring this intersection of technology and pedagogy, the paper will provide a comprehensive understanding of the pivotal role Augmented Reality plays in catalyzing the digital transformation of education.

2.2 Components of digital transformation

Digital transformation in education comprises a multitude of components, each of which plays a crucial role in shaping how teaching and learning processes evolve in the 21st century.

To start, technology infrastructure is foundational to digital transformation in education. This encompasses both hardware, such as computers, tablets, interactive whiteboards, and AR/VR devices, and software, including Learning Management Systems (LMS), educational apps, and digital content platforms. For instance, schools are increasingly leveraging cloud-based LMS like Google Classroom to facilitate efficient communication, manage assignments, and provide a centralized location for resources [5]. Additionally, Augmented Reality technologies can be considered to be a fascinating choice for educators seeking resources and methods to stimulate their students about the topic they teach. In recent years, the increasing number of relevant educational applications indicates that this new technology has the potential of becoming a leading educational method in schools and universities [2,10].

Furthermore, the emergence of big data and analytics is dramatically changing educational processes. These technologies allow for the collection and analysis of vast amounts of information regarding student performance and learning patterns. Data-driven insights can be used to personalize instruction, improve curriculum design, and enhance decision-making processes in educational institutions [6].

Another vital component is the proliferation of Artificial Intelligence (AI) in education. AI's impact spans from automating administrative tasks to supporting personalized learning. For instance, AI-powered chatbots can serve as virtual teaching assistants, responding to common student inquiries and thereby freeing up time for educators [7]. Moreover, AI-based adaptive learning platforms can tailor educational content to individual learner's needs, offering a more personalized and efficient learning experience [5,13].

Next, digital transformation has ushered in an era of increased connectivity and collaboration [2]. With the help of collaborative platforms and tools, students are no longer bound by the four walls of a classroom. They can collaborate on projects with peers across the globe, thereby fostering a more interconnected and global learning environment [15].

2.3 The role of digital transformation in Education

The role of digital transformation in education has become increasingly pivotal in the recent years, spanning from primary to higher education learning (Figure 2).

Figure 2 - Digital transformation from Primary to Higher Education

The advent of emerging technologies such as AR, VR, MR and 5G networks has catalyzed this shift, ushering in an era of enhanced learning experiences that are more interactive, engaging, and personalized [1,2,4,15,16].

Figure 3 - Digital Transformation in Classroom - Enhance learning using AR

AR, in particular, has revolutionized the conventional classroom environment, transforming it into an immersive learning space. Through mobile applications, students are now able to explore complex concepts in a three-dimensional, interactive manner right from their devices (Figure 3) [4,15]. This transformation goes beyond the use of technology in learning, it extends to the design and equipment of the classrooms, making them digitally equipped learning environments.

Moreover, 5G networks, with their high-speed and low-latency capabilities, have made real-time AR or live streaming experiences more accessible and efficient. This progression has expanded access to education, removing geographical and logistical barriers to quality learning [17,18].

Furthermore, digital transformation has enabled personalized learning, where the learning pace, style, and content can be tailored to individual students. It also aids in strengthening cooperation through collaborative digital platforms that foster effective group learning. Lastly, digital transformation has drastically improved assessment and feedback processes, making them quicker, more consistent, and significantly more effective [15].

2.3.1 Transformation of educational spaces and equipment

The way we design and use educational spaces has been changing rapidly due to advances in technology. This change isn't just about using more tech tools in teaching, but it's also about the physical layout and equipment in classrooms, labs, and school buildings [15].

Figure 4 - Digital transformation - From traditional to modern Edu spaces

Today's classrooms are built with the latest tech trends in mind. Old-fashioned blackboards and stationary desks are being replaced with interactive screens and flexible furniture that can adapt to different learning methods. Many classrooms and libraries are now equipped with digital tablets, laptops, and high-speed internet connections [2,16]. Also, thanks to tech advances, we're seeing the rise of 'smart classrooms'. These rooms are filled with Internet of Things (IoT) devices that make digital communication easy, tools that use augmented reality to create immersive learning experiences, and cloud systems that let us store and access educational resources (Figure 4) [4,16]. These changes are turning physical learning spaces into digitally-enhanced environments that are perfect for today's tech-savvy students.

2.3.2 Transformation of teaching and learning methods

Schools and institutions, especially after the pandemic, are now integrating technologies like Zoom and Google Meet or Microsoft Teams into their platforms to establish digital classrooms that merge multiple technologies [18,19].

AR/VR are expanding their footprints in the education sector. For instance, A noteworthy example is the Aurasma application utilized by St. Stephen’s Primary School in the UK. The school integrated AR technology to enhance teaching and learning experiences. By using the Aurasma app, students could scan their drawings and turn them into animations [20]. Similarly, gamification enhances knowledge retention in children, slowly percolating into professional training and examination domains.

Moreover, the digital examination portals pose a solution to traditional assessment hurdles. To maintain academic integrity, online exam portals now incorporate webcam monitoring to detect any suspicious activities during exams [21]. The teacher's role is also evolving, becoming a facilitator in a technology-enriched environment [22]. By integrating the Internet of Things (IoT) in schools, this transformation is driven to deepen further, steering education towards a smarter future.

2.3.3 Benefits of digital transformation in Education

The benefits of digital transformation in education are significant and far-reaching, proving the potential of technology in reshaping the educational environment [1.4,23].

In summary, digital tools such as artificial intelligence and machine learning provide tailored learning routes in elementary and secondary school. This implies that instructors may fine-tune their teaching tactics to each student's particular needs and talents, establishing an atmosphere that enhances understanding and engagement [4,24]. Furthermore, the introduction of AR and VR adds an aspect of immersion and tangibility to teaching. Modern lessons are a reality for instance: a biology lecture in which students may explore the human body in 3D or a history lesson in which they can virtually travel to past civilizations - these are the opportunities that AR and VR provide, making learning more engaging and transformational [6,25].

In higher education, digital transformation transforms research procedures and supports academic growth through data analysis and predictive modeling. Online educational platforms allow fair access to high-quality learning resources, expanding education's reach beyond conventional geographical limits. Such digital inclusion allows learners all around the world to benefit from the intellectual resources of famous educational institutions [6,26]. Furthermore, digital change extends beyond the boundaries of individual classrooms, building a global learning community. Digital technologies promote cooperation by allowing students from various backgrounds to exchange ideas and learn from one another, so boosting cultural understanding and global consciousness. Furthermore, digitally improved evaluation and feedback systems provide instructors with a detailed view of student development, allowing them to alter teaching tactics for the best learning outcomes [2,20,27].

The rise of digital tools in the classroom is not just a passing trend; rather, it represents a dynamic drive toward a significantly enhanced educational experience [15,28]. The next chapter will focus on AR technology, taking a cursory look at its history, classifications, and available tools for AR creation.

2.3.4 Challenges of digital transformation

The journey towards digital transformation in education, while replete with promise and potential, is also fraught with numerous challenges.

One of the most pressing issues relates to the digital divide and the inequity in access to digital tools and internet connectivity, which has been made evident during the COVID-19 pandemic. According to the United Nations, as of 2020, at least 463 million students globally were unable to access remote learning due to a lack of digital resources, thus posing a significant barrier to digital transformation [29]. Additionally, teachers often face the daunting task of rapidly upskilling to effectively use and integrate new technologies into their instruction. There is a need for comprehensive professional development and support to ensure educators are comfortable and competent in these digital environments [29]. Data privacy and security are further hurdles in the digital landscape. Protecting students' personal information and ensuring the security of online platforms has become a critical concern, particularly with the increased usage of digital tools for learning and communication [30,31,32].

From an equipment perspective, deploying digital technology requires every student to have access to a suitable device, such as a laptop, tablet, or even a smartphone, for specific applications. Not all students may possess these devices, and procuring them can be a cost-intensive process for schools or parents. Additionally, these devices need to be regularly updated and maintained which incurs additional costs and effort [31,32]. Moreover, proper digital education requires robust, reliable, and fast internet infrastructure. Schools need to ensure a stable internet connection throughout their premises to support online learning activities. Rural areas or low-income regions often suffer from insufficient connectivity, hindering digital transformation efforts [33].

The initial cost of setting up digital classrooms is considerable. Besides hardware, substantial investment is required for software licenses, staff training, and possibly even building renovations to accommodate new technology. Recurring costs include subscriptions for educational software, cloud services, tech support, and continuous training for staff [34]. In addition, adopting emerging technologies such as Augmented Reality and Virtual Reality further compounds these challenges. These technologies require specialized equipment and high-speed internet connections, and their incorporation involves a steep learning curve for educators and students alike [35].

While grants and other funding opportunities are available to assist with these costs, they may not be accessible to all institutions, creating a digital divide that can exacerbate existing educational inequalities. Without clear planning and support from leadership, digital initiatives risk being disjointed and less effective [30,32].

Moving forward, the subsequent chapter offers an in-depth exploration of Augmented Reality - the technology that is rapidly redefining the boundaries of digital transformation in education.

3
EXPLORING AUGMENTED REALITY – FROM ORIGINS TO APPLICATIONS

As we transition from the discussion on digital transformation in education in the preceding chapter, we now turn our attention towards an emerging technology that stands at the forefront of this transformation: Augmented Reality.

In this chapter, we provide a detailed exploration of AR - from its origins to the multitude of its applications. Beginning with the history of AR, we explore its evolution and how it has shaped the technology we interact with today. This leads us into the distinction between AR, VR and MR, illuminating their unique characteristics and applications. Next, we delve into the different categories of AR, splitting them into hardware-based, software-based, and application-based categories. Each of these subsections provides insight into various aspects of AR such as Optical See-Through (OST) displays, Video See-Through (VST) displays, marker-based and markerless AR, and the applications of AR in industries like healthcare, education, and entertainment. The chapter then pivots to discuss the different software available for AR development, examining popular tools such as ARCore, ARKit, Vuforia, MRTK and Unity MARS

Finally, we draw comparisons between these software tools in a comprehensive table, aiding readers in understanding the pros and cons of each platform and helping them make informed decisions about which software would best suit their AR development needs. In summary, this chapter offers a comprehensive overview of the fascinating world of AR, paving the way for its application in the field of education.

3.1 History

The history of augmented reality (AR) is a fascinating journey of technological advancements that spans decades.

The conception of AR can be traced back to the early 1960s with three-dimensional displays at MIT, Sutherland. Ivan Sutherland was the person who developed the first Head Mounted 3D Display (HMD) as shows the following figure (Figure 5) [42,43]

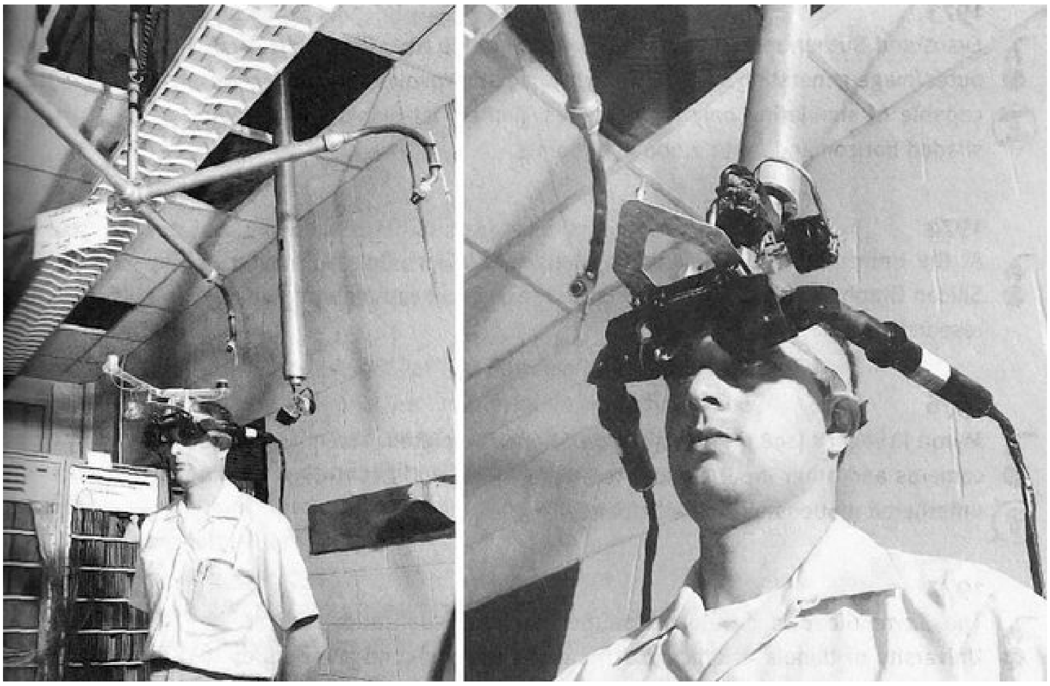

Figure 5 - Ivan Sutherland (1960s) – The first 3D Display HMD

In 1975 Myron Kruegar created the responsive environment of the Videoplace Lab (Figure 6) and in the early of 1980s, Steve Mann focused on research and developments that influenced the future of AR. [42,43]

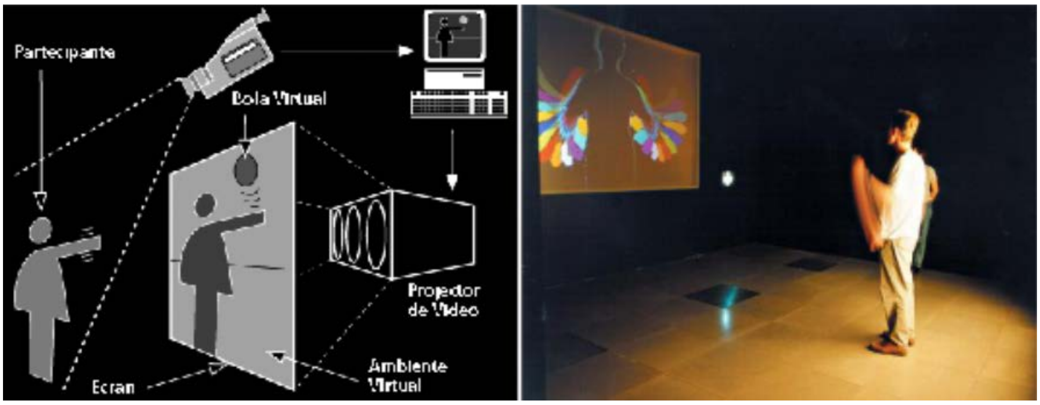

Figure 6 - Myron Kruegar (1975), Videoplace Lab

AR technology also came to the surface with the inception of Virtual Fixtures, an AR system developed by the U.S. Air Force, though the field truly began to flourish in the early 21st century [35]. Specifically, the term "augmented reality" was coined by Boeing researcher Tom Caudell in 1990. By 1992, Louis Rosenberg created the first fully immersive AR system at the U.S Air Force Research Laboratory. Then, in 1998, augmented reality was first used for navigation, in NASA's X-38 spacecraft (Figure 7). [35,42,43]

Figure 7 - 1998, AR was first used for navigation, in NASA's X-38 spacecraft

The rapid technological progress of the 2010s ushered in a new era for AR. The first significant breakthrough came in 2013 with the launch of Google Glass, a wearable computer with an optical head-mounted display that brought the potential of AR to the mainstream. Although Google Glass faced initial setbacks, its concept laid the foundation for future developments [36].

In 2016, the commercial potential of AR became indisputable with the success of the mobile game Pokémon Go. With over 500 million downloads worldwide in the first year of its launch, the game demonstrated the vast potential of AR in captivating a broad audience and creating immersive experiences [37]. Undoubtedly, an important segment of the market is mobile AR, taking advantage of the vast number of smartphones, tablets, and other mobile devices the global population owns or has access to. As per recent data, in the end of 2023, there will be an estimated 1.4 billion mobile AR users worldwide and is forecast to grow to 1.73 billion by 2024 as Figure 8 shows [41].

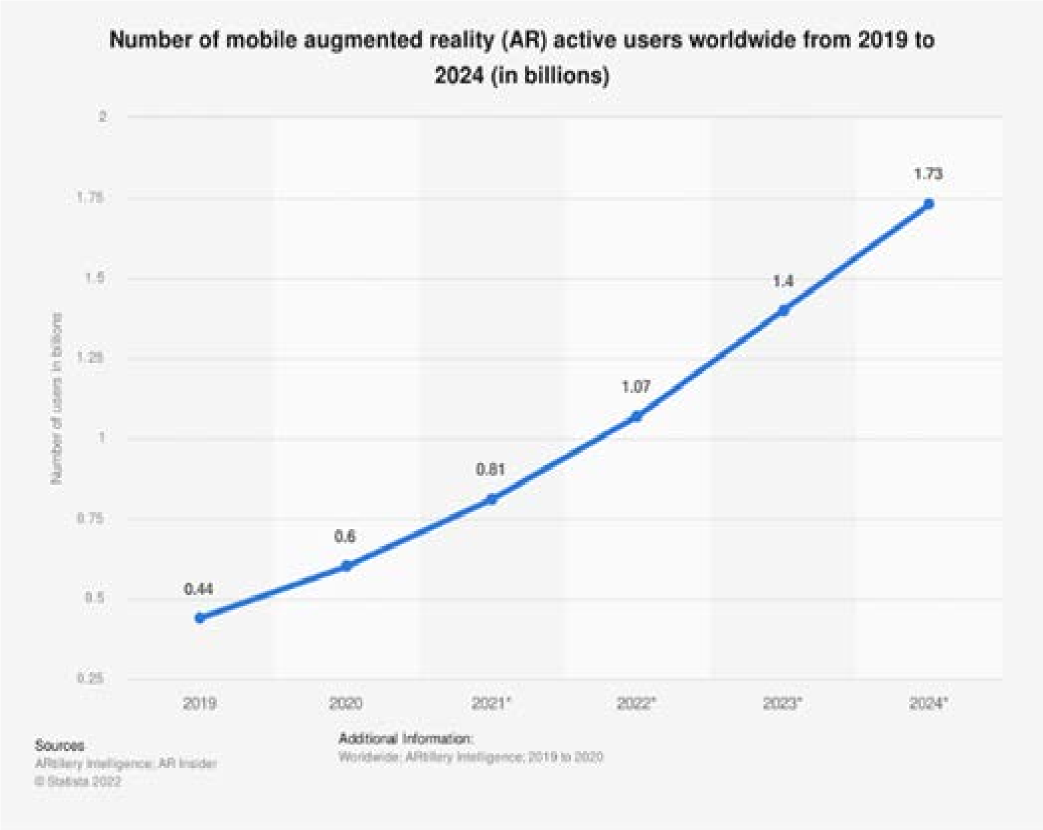

Figure 8 - Number of mobile augmented reality (AR) active users worldwide from 2019 to 2024 (in billions)

Simultaneously, AR began gaining momentum in various industries, including healthcare, manufacturing, and education. The development of AR applications for surgical procedures, remote maintenance and repair, and interactive learning environments, marked the transition of AR from a novel concept to a practical tool [36,37].

Hardware advancements also played a significant role in AR's progress. The release of devices such as Microsoft's HoloLens in 2016 and Magic Leap One in 2018, which utilized Optical See-Through (OST) displays, provided sophisticated platforms for AR applications. These devices, coupled with the continuous enhancement of smartphone capabilities, paved the way for the widespread accessibility and applicability of AR [38].

As the technology of AR matures, it promises to reshape our interaction with the digital world, merging the physical and virtual realms in unprecedented ways.

3.2 Differences of AR / VR / MR

Subchapter 1.4 previously provided a concise introduction to Augmented Reality, Virtual Reality, and Mixed Reality technologies, clearly defining their basic distinct functionalities and primary objectives.

Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR) are separate but interrelated technologies, each offering unique experiences and capabilities. As mentioned, AR involves superimposing digital information, such as images, sounds or data, on the real world, thereby 'augmenting' the user's perception of reality.

With AR, users remain engaged in their physical environment while interacting with virtual elements. Smartphone applications, for example, social media applications that include AR camera filters in social media platforms, are a prime example [2,39,40].

In contrast, VR immerses the user in a completely virtual environment that is disconnected from the physical world. Users can explore and interact with a computer-generated reality through a VR headset, such as virtual tours or simulated training environments [39,40,42].

MR is a hybrid of AR and VR that integrates virtual objects into the real world in such a way that they interact with the physical environment, providing a blend of both realities. MR devices, such as Microsoft's HoloLens, allow users to manipulate virtual objects and interact with them as if they were real [41,42].

While the technologies share similarities, the fundamental difference lies in how each handles the user's perception of reality. As AR, VR, and MR technologies improve, the spectrum of real-world-virtual interactions will expand [2,42,43].

The following table (Table 2) compares the key aspects of AR / VR / MR technologies. It captures their definitions, modes of interaction, hardware requirements, and diverse applications having the goal to highlight their unique attributes and differences while also showcasing their converging points.

	Augmented Reality	**Virtual Reality**	**Mixed Reality**
Definition	Overlays digital information onto the real world.	Creates a completely virtual environment, independent of the real world.	Blends real and virtual worlds, allowing interaction between physical and digital objects.
Interaction	Users interact with virtual elements while staying aware of their physical environment.	Users are immersed in and interact with a computer-generated environment.	Users can interact with virtual objects as if they were part of the physical world.
Hardware	Usually smartphones, tablets, or AR glasses.	VR headsets such as Meta Quest Pro or Sony PlayStation VR2	MR devices such as Microsoft HoloLens.
Applications	Gaming, marketing, design, education.	Gaming, healthcare, training simulations, education.	Design, collaborative work, gaming, education.

Table 2 - AR / VR / MR - Definition, Interaction, Hardware, Applications

3.3 Categories of Augmented Reality

In the ever-changing Augmented Reality (AR) ecosystem, categorizations occur primarily around hardware, software, and application viewpoints. Each brings a unique perspective to our knowledge and implementation of augmented reality technology, whether via various hardware devices, creative software solutions, or the varied sectors of application ranging from education to entertainment [44].

3.3.1 Hardware-based Categories

The hardware-based category in Augmented Reality (AR) involves physical devices employed to deliver AR experiences. These primarily include Optical See-Through (OST) and Video See-Through (VST) displays [45,47].

3.3.1.1 Optical See-Through (OST) Displays

OST displays maintain the user's direct view of the physical environment, using semi-transparent mirrors or beam splitters to superimpose computer-generated imagery onto the user's field of view [46].

Two key types of OST devices are Head-Mounted Displays (HMDs) and glasses-style devices. The Microsoft HoloLens is a notable example of an HMD, providing a hands-free, immersive AR experience. On the other hand, glasses-style devices, such as Google Glass, offer a less immersive but more lightweight and socially acceptable format [44,46,47]. The design and optimization of OST displays involve challenges related to image alignment, field of view, depth cues, and occlusion handling. Addressing these challenges constitutes a critical area of ongoing research and development in AR technology.

3.3.1.2 Video See-Through (VST) Displays

Video See-Through (VST) technology serves as an accessible means to deliver Augmented Reality (AR) experiences.

VST works by using a camera to record a digital image of the surrounding world, which is then delivered in real-time to a graphics engine. The processor combines the video input with virtual material created by computers and displays the resulting composite picture on the screen. Given that video processing takes place before user contact, it is possible to modify the contrast and brightness of both the actual and virtual components to create a seamless user experience. Additionally, it guarantees improved registration by monitoring head motions. However, it has some drawbacks, such as the reduced resolution of the reality depicted (because screens cannot match human eye resolution), a limited field of view (expandable, but at a high cost), and problems with eye parallax (eye-offset) because the camera is typically placed away from the viewer's exact eye location [45,46,47].

In devices like the Samsung Gear VR (Figure 9), a VST application may be shown where the phone, acting as a display, is placed a few inches away from the user's eyes - a situation radically different from the experience of AR on handheld smartphones.

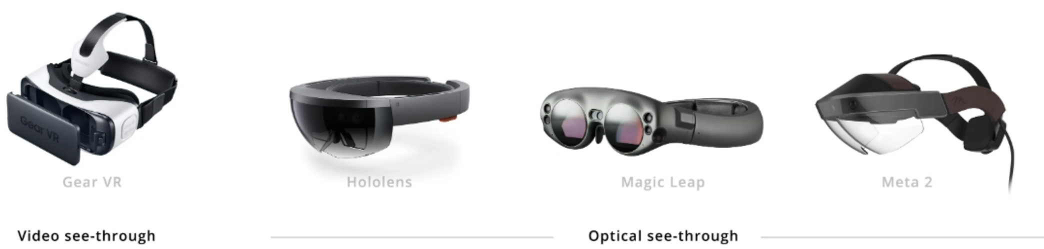

Figure 9 - Popular VST and OST headsets in the market

3.3.1.1 VST / OST Comparison

Video See-Through (VST) and Optical See-Through (OST) technologies serve as integral components of Augmented Reality (AR) systems [45]. VST, which merges real-world video images with computer-generated graphics, offers control over brightness and contrast, but faces challenges with resolution and field of view [45,47]. OST, in contrast, uses semi-transparent devices to overlay digital content onto the physical environment, enabling immersive experiences. However, it contends with image alignment and depth cue issues [47]. The following figure (Figure 10) illustrates the main differences.

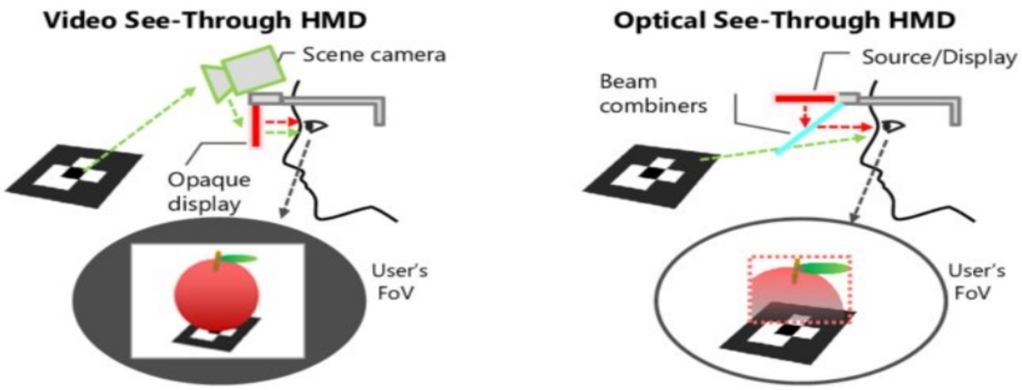

Figure 10 - Comparison of VST and OST displays

3.3.2 Software-based Categories

Another type of categorization of AR is based on software methodologies, particularly focusing on Marker-based and Markerless AR technologies.

Marker-based AR relies on physical markers in the environment to trigger and anchor digital content. Conversely, Markerless AR capitalizes on sensors, algorithms, and geographical data to seamlessly merge virtual elements into the user's real environment. These software-driven techniques have been instrumental in enabling a wide spectrum of AR applications across numerous fields [2,48]

3.3.2.1 Marker-based AR

Marker-based AR systems monitor and place virtual material inside the actual world by using physical markers like fiducial markers or QR codes [2,37]. To identify and follow markers, these systems depend on image processing and computer vision techniques. AR that uses markers is often utilized in marketing, instruction, and entertainment.

3.3.2.2 Markerless AR

Markerless augmented reality systems do not need physical markers and instead depend on natural elements to place virtual material [2]. Examples of natural features that may be used include patterns and textures. These systems often include methods known as simultaneous localization and mapping, or SLAM, in order to generate a three-dimensional map of the surrounding area. This makes it possible for virtual content to be correctly positioned inside the physical world. Applications like as gaming, navigation, and interior design are seeing increased use of markerless augmented reality [2,37].

3.3.2.3 Marker-based AR / Markerless AR comparison

The main difference between two technologies is that Marker-based AR employs physical markers as triggers for positioning digital content. Contrarily, Markerless AR utilizes sensors, algorithms, and geographic data to incorporate virtual elements into the user's surroundings, without the need for specific markers [2].

The following comparison table (Table 3) is more descriptive and detailed regarding the differences of two technologies and give a better understanding.

Criteria	**Marker-Based AR**	**Markerless AR**
Initialization	Requires predefined markers like QR codes or images	Uses features of the environment recognized by sensors
Position Accuracy	High; defined markers ensure precise digital overlay	Varies; dependent on sensor accuracy and algorithm efficiency
Environment Preparation	Needs preparation in marker placement	None required; works with natural and built environments
Real-time Performance	Very effective due to marker recognition	Can be complex due to real-time environmental analysis
Use Cases	Ideal for controlled environments like education, advertising, gaming	Suitable for dynamic environments like navigation, indoor design, games

Table 3 - Marker-based AR / Markerless AR comparison

From the comparison table, it is evident that Marker-Based AR and Markerless AR offer distinct advantages and challenges. While Marker-Based AR provides high position accuracy and effective real-time performance, it requires an environment preparation through marker placement. On the other hand, Markerless AR offers high flexibility with no need for prior environment preparation, but the position accuracy and real-time performance are dependent on sensor accuracy and computational algorithms.

3.3.3 Application-based Categories

Applications of AR in industries such as manufacturing, healthcare, education, and entertainment have shown the technology's potential to improve human interaction with both physical and digital settings.

Industrial augmented reality is causing a revolution in the processes of production and design by offering real-time data and support in performing complicated activities, hence increasing productivity and lowering mistake rates. AR is being used in the medical field to help with delicate surgical operations, medical training, and patient care. It does this by providing visuals that is normally difficult to attain. AR has a transformational role to play in education, with the ability to produce immersive learning experiences that boost both understanding and engagement. Entertainment is another industry where augmented reality has developed immersive experiences. These experiences may be found most notably in gaming, films, and location-based attractions, and they provide customers with material that is both interactive and interesting [4]. The majority of Augmented Reality (AR) applications today are focused on mobile devices, primarily due to their ubiquity and convenience

3.3.3.1 Industrial AR

Industrial AR applications enhance manufacturing, maintenance, and training processes by providing real-time, context-aware information to users. Examples include assembly guidance, remote assistance, and machinery maintenance. Industrial AR improves efficiency, reduces errors, and enhances worker safety [49].

3.3.3.2 Healthcare AR

Healthcare AR applications utilize AR technology to support medical professionals in diagnostics, treatment, and training. Examples include surgical navigation, medical imaging visualization, and patient education. Healthcare AR has the potential to improve patient outcomes, increase accuracy, and reduce medical errors [50].

3.3.3.3 Education AR

The provision of material that is interactive, immersive, and engaging is made possible by augmented reality apps for use in educational settings [51,52]. These programs make it possible to visualize difficult ideas, mimic situations that could occur in the real world, and foster collaborative learning. It has been shown that using AR in education may enhance students' ability to retain information, as well as their motivation and engagement levels. The next main chapter will focus specifically on the role of AR in Education.

3.3.3.4 Entertainment AR

Entertainment augmented reality apps provide fully immersive and interactive experiences for a variety of uses, including gaming, social networking, and creative expression [51]. These apps often incorporate interaction in the real world as well as multiplayer experiences, merging digital and actual engagement. The rise in popularity and general understanding of AR technology has been considerably aided by the use of AR into entertainment [52].

3.4 Augmented reality development software

As the AR technology has emerged as a potent tool in transforming the ways we interact with the digital world, the proliferation of AR applications in sectors like gaming[3], education, healthcare, and e-commerce is attributed to the sophisticated development software that facilitate the design of immersive experiences [53][54].

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[3] Pokemon GO AR Application became the first location-based AR game to garner mainstream popularity and one of the most successful mobile games in general. The game had reached over 750 million downloads worldwide within its first year and had made $1.8 billion in revenue with in-app purchases in two years [58].

This development software includes toolkits such as ARKit for iOS, ARCore for Android, and cross-platform tools like Unity3D and Unreal Engine. They provide the necessary frameworks for constructing AR experiences, encompassing elements like image recognition, 3D modeling, and geolocation [55][56].

To leverage these tools effectively, developers need a solid understanding of computer vision, 3D programming, and machine learning [57]. This section will present some well-known, widely used and mostly open-source AR development software, focusing on their special characteristics.

3.4.1 ARCore

ARCore is Google's platform for building AR experiences on Android devices (Figure 11 & Figure 12) [59]. It leverages three main capabilities - motion tracking, environmental understanding, and light estimation to merge digital content with the real world [60]. These features help in creating engaging AR experiences, such as Google's "Just a Line" application, where users draw in the air with AR. A research paper by J. Linowes and K. Babilinski, compared ARCore with other AR platforms, analyzing its strengths and limitations [61,59].

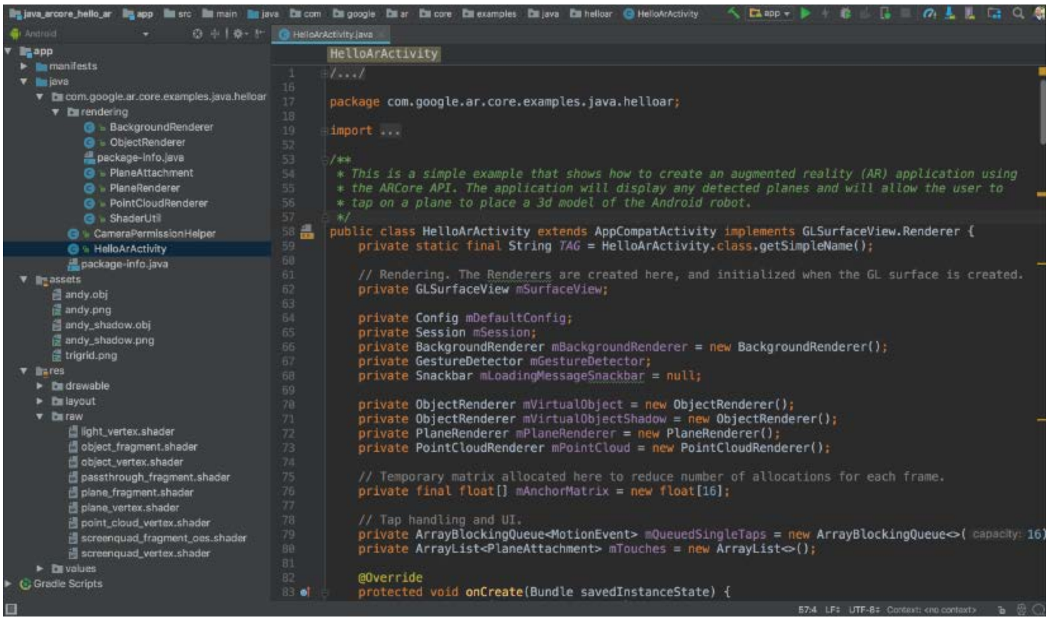

Figure 11 - ARCore development on Android Studio for Android Apps - Run of hello_ar_java

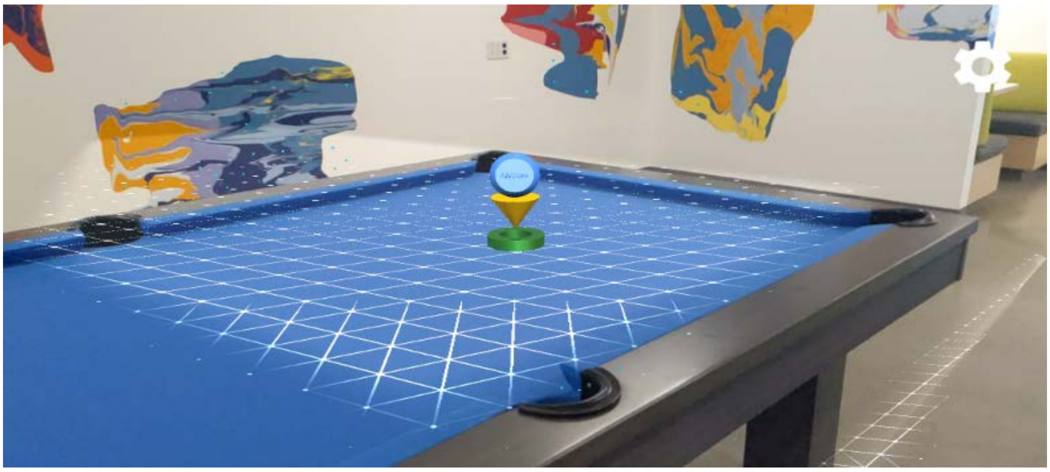

Figure 12 - hello_ar_java app let users place a 3D ARCore pawn on detected AR plane surfaces

3.4.2 ARKit

Apple's ARKit provides a robust framework for developing AR applications for iOS devices (Figure 13). ARKit uses Visual Inertial Odometry (VIO) and plane detection for accurate tracking and environmental understanding [62]. ARKit has found extensive applications in fields like gaming, shopping, and industrial design. A notable example is IKEA Place, an AR app that enables users to preview furniture in their homes [63].

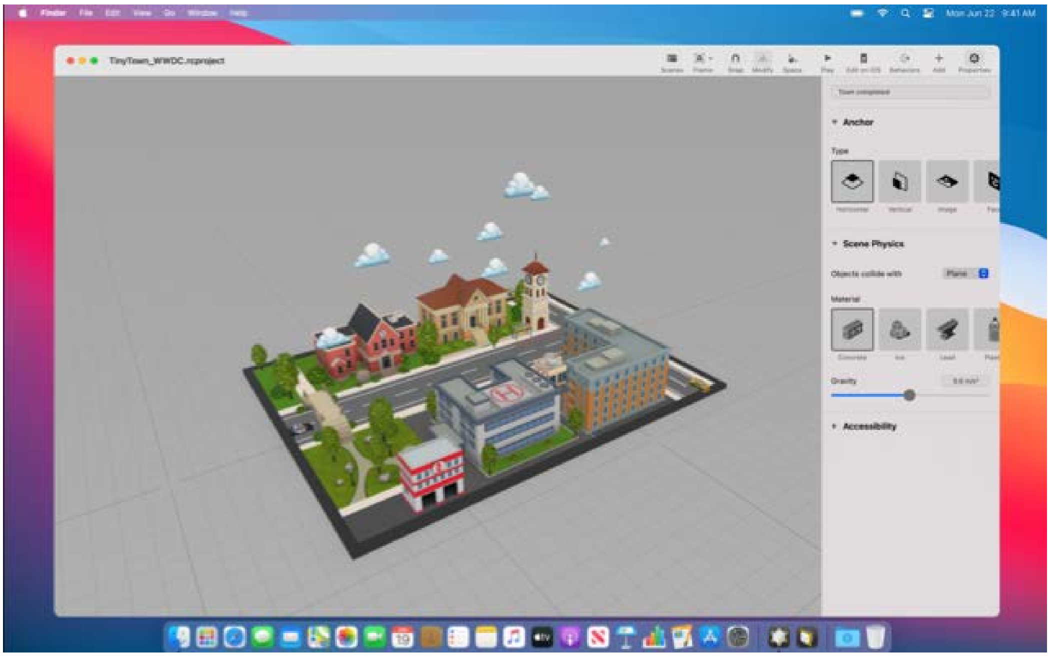

Figure 13 - AR Development in ARKit

3.4.3 Vuforia

Vuforia is a widely used AR software development kit (SDK) developed by PTC Inc. It supports image recognition, 3D object tracking, and environment sensing, which enhances AR interactivity and immersion [64]. A research by L. Zhang et al. provides an example of using Vuforia for creating an AR-based apps (Figure 14) [65,3].

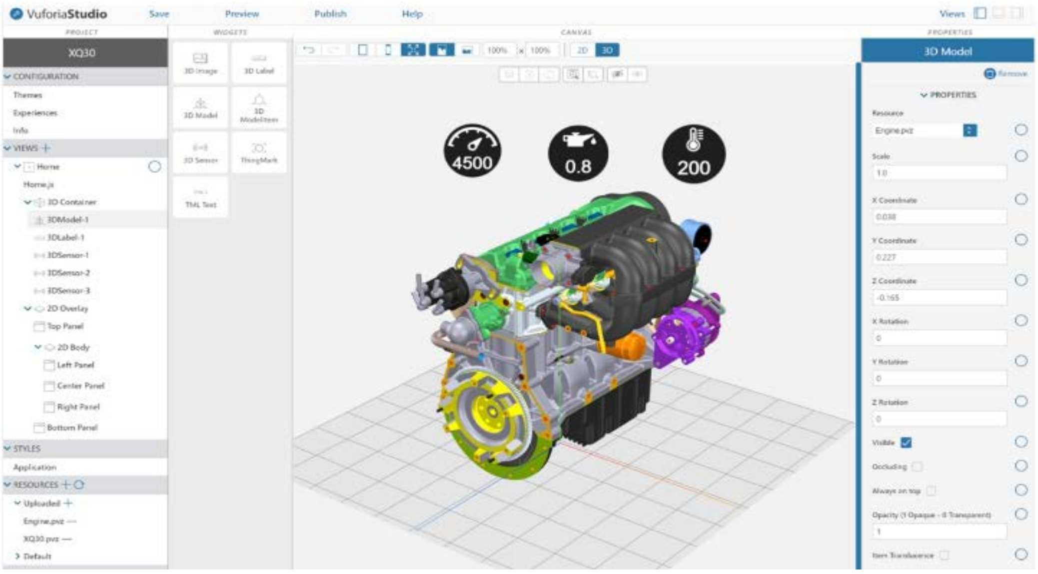

Figure 14 - AR Development in Vuforia Studio

3.4.4 Microsoft Mixed Reality Toolkit (MRTK)

MRTK is an open-source, cross-platform development kit for mixed reality applications (Figure 15). It provides a set of components and features to accelerate the development of holographic applications in Unity [66]. A study by Bower et al. explores its applications in creating immersive learning environments [66].

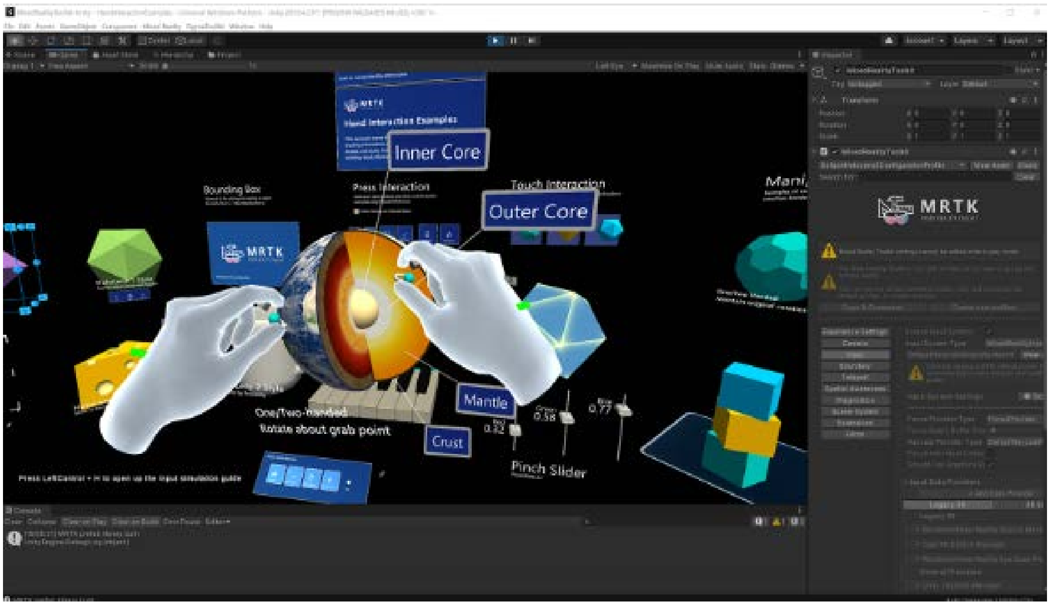

Figure 15 - AR Development in MRTK

3.4.5 Unity MARS

Unity MARS (Mixed and Augmented Reality Studio) provides developers with specialized tools for creating robust AR experiences especially in gaming industry that fully interact with the real world (Figure 16). The software features world tracking, plane finding, face tracking, and other functionalities [67]. Costa et al. utilize Unity MARS to develop an AR application for the visualization of cardiac coherence [68].

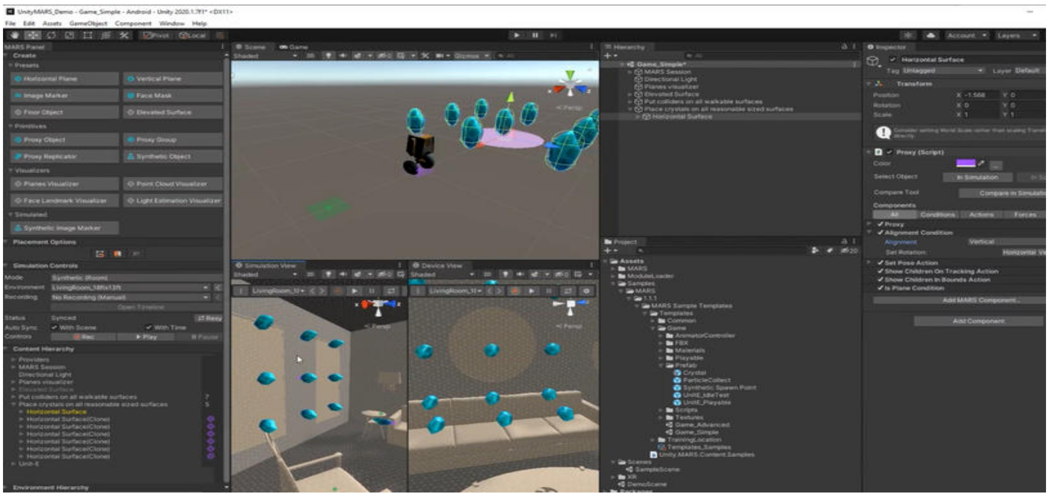

Figure 16 - AR Development in Unity MARS

3.4.6 Amazon Sumerian

Amazon Sumerian is a web-based platform for creating high-quality virtual reality (VR) and AR experiences (Figure 17). It provides features like a visual scripting tool and AI services integration, which enable the development of interactive 3D scenes [69,70].

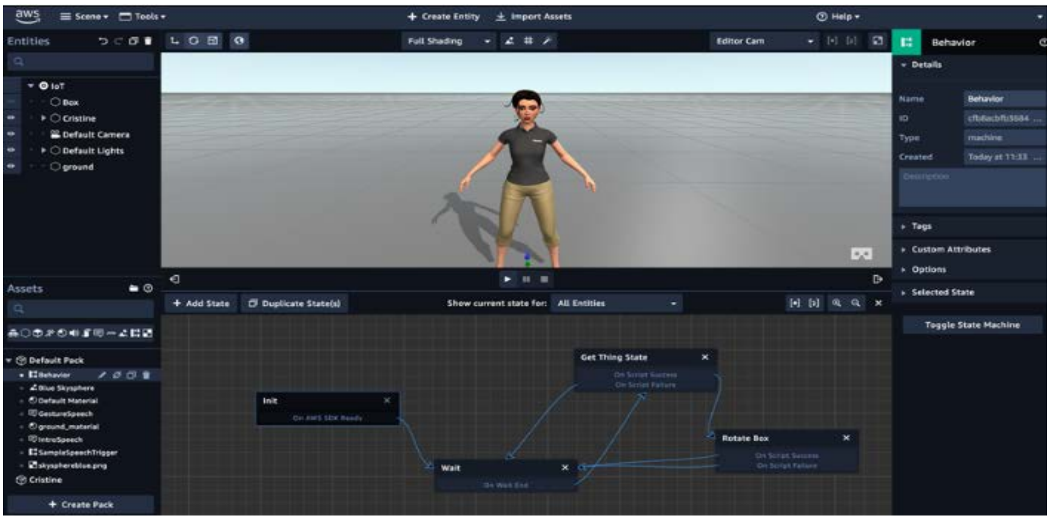

Figure 17 - AR Development in Amazon Sumerian

3.4.7 A-Frame

A-Frame is a web framework for building virtual reality (VR) experiences. A-Frame makes it easy for web developers to create VR experiences using HTML, and it supports most AR and VR headsets (Figure 18) [71]. An example of A-Frame's use in educational settings is provided in this study [72].

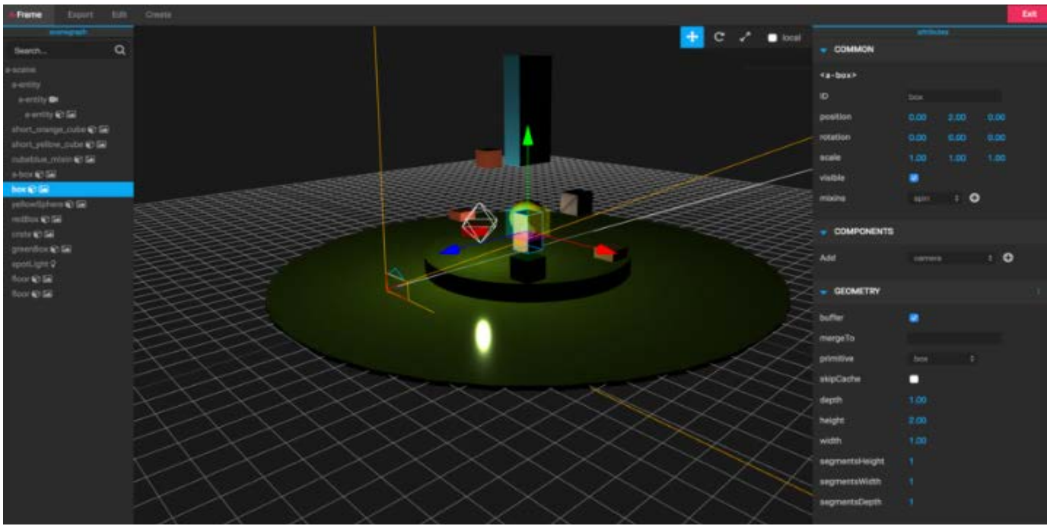

Figure 18 - AR Development in A-Frame

3.4.8 8th Wall

8th Wall is an AR platform that lets developers use a single codebase to create AR experiences across different platforms. One significant advantage is its ability to enable AR in web browsers, allowing users to engage with AR content without downloading specific apps (Figure 19) [73].

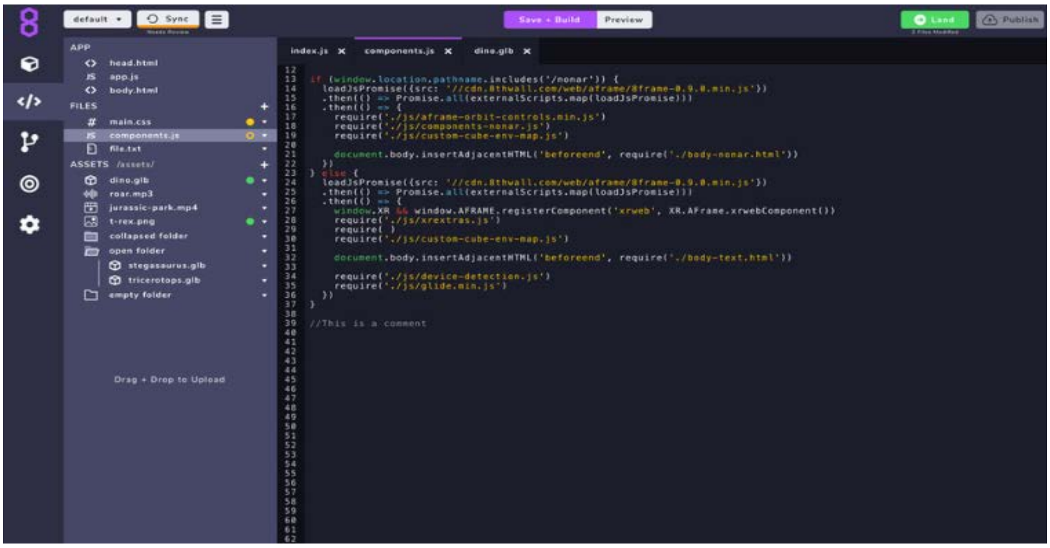

Figure 19 - AR Development in 8th Wall

3.4.9 Wikitude

Wikitude is a mobile AR technology provider enabling apps to see, understand, and augment the world in real-time on smartphones, tablets, and smart glasses (Figure 20) [74]. The research by D. Amin and S. Govilkar, [75] details an application of Wikitude in AR-based navigation systems.

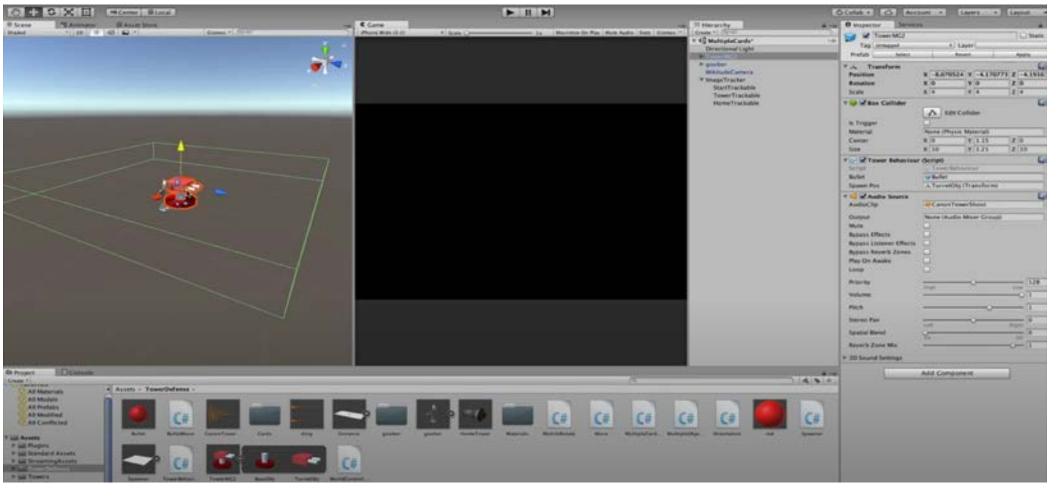

Figure 20 - AR Development in Wikitude

3.4.10 ZapWorks

ZapWorks is an AR creation toolkit developed by Zappar. The toolkit includes three different tools for developers with different levels of expertise: Designer for beginners, Studio for more advanced developers, and Universal AR for developers familiar with JavaScript frameworks (Figure 21) [76,77]. One example of its usage is for enhancing interactive storytelling in education.

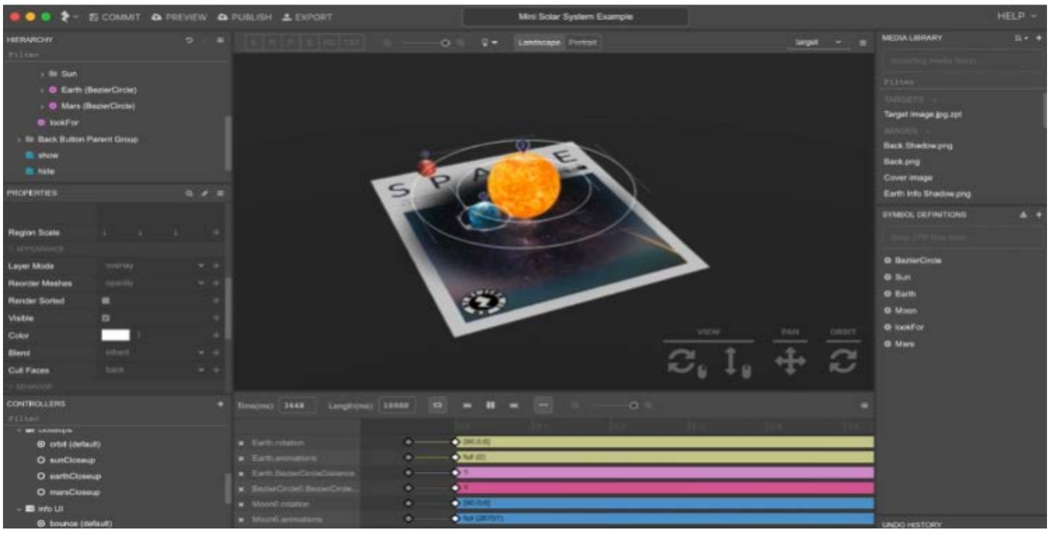

Figure 21 - AR Development in ZapWorks

3.4.11 Magic Leap

Magic Leap is a spatial computing platform that enhances the perception of digital content in the physical world (Figure 22) [78,79]. It is designed for creating and viewing MR experiences with the Magic Leap 1 & 2 headset especially for the learning enviroments.

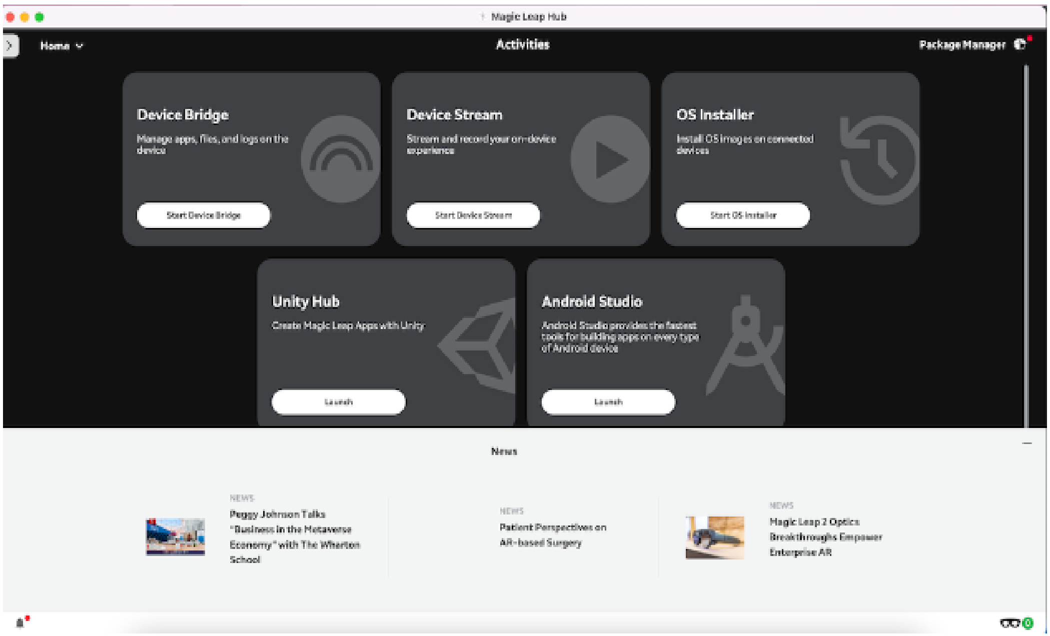

Figure 22 - AR Development in Magic Leap

3.5 AR comparison table for the AR development

Here is a comparison table for the AR development software we discussed. The following table provides a comparison of eleven key AR development software tools. These tools have varied capabilities and advantages, and are suited to different platforms and operating systems. Understanding these differences is essential for selecting the appropriate tool for a given AR project for any purpose, from educational to business one.

According to comparison table (Table 4), it is evident that the choice of AR development software largely depends on the specific requirements of the project. For projects that prioritize depth perception and lighting estimation, Google's ARCore is an ideal choice. If the project aims to develop AR applications for iOS with excellent scene understanding and rendering, Apple's ARKit is a strong contender.

On the other hand, if the project requires object recognition or needs to be compatible across Android, iOS, and UWP, Vuforia offers these capabilities. Microsoft Mixed Reality Toolkit (MRTK) has its strengths in supporting HoloLens 2 and offering a variety of input systems. Unity MARS extends the capabilities of Unity, focusing on creating responsive AR experiences.

AR Development Software	Supported Platforms	Web AR Capabilities	Specific Strengths	Cost
ARCore	Android, Unity	No	Depth API, lighting estimation	Free
ARKit	iOS, Unity	No	Scene understanding, realistic rendering	Free
Vuforia	Android, iOS, UWP, Unity	No	Object recognition, wide platform support	Free with Paid Plans
Microsoft Mixed Reality Toolkit (MRTK)	Unity, UWP	No	HoloLens 2 support, variety of input systems	Free
Unity MARS	Unity	No	Scene understanding, responsive AR design	Paid
Amazon Sumerian	Web-based	Yes	Integration with AWS services	Free Tier with AWS Charges
A-Frame	Web-based	Yes	Accessible VR/AR creation with HTML	Free
8th Wall	Web-based	Yes	Cross-platform, web-based AR	Free with Paid Plans
Wikitude	Android, iOS, Smart Glasses, Unity	Yes	Image recognition, location-based AR	
ZapWorks	Android, iOS, Web-based	Yes	Ease of use, creative tools	Free with Paid Plans
Magic Leap	Magic Leap 1 headset	No	Spatial computing, immersive experience	Paid

Table 4 - AR comparison table for the AR development software

For developers seeking to create AR applications integrated with Amazon Web Services, Amazon Sumerian serves this purpose. If the project demands creating AR experiences directly in a web environment, A-Frame, 8th Wall, and ZapWorks have strong offerings, while Wikitude excels in image recognition and location-based AR.

Finally, Magic Leap provides a unique approach to AR, offering spatial computing capabilities for an immersive experience, particularly when used with the Magic Leap 1 headset. However, for educational purposes for teaching and learning when someone (maybe a teacher) is considering the cost factor along with the capabilities of each AR development software, the choice becomes even more nuanced. For instance, Google's ARCore and Apple's ARKit, both providing significant features for AR development, stand out as they are free to use and support Android and iOS platforms respectively.

Similarly, A-Frame offers a cost-effective solution for developers seeking to create AR experiences directly in a web environment. Amazon Sumerian also provides a competitive solution, especially for those already leveraging AWS services, although developers need to consider AWS charges beyond the free tier.

In contrast, Vuforia and 8th Wall, despite their powerful features, operate on a freemium model, meaning certain advanced features come at a cost. The same applies to ZapWorks, which offers a range of creative tools for AR development. Unity MARS, Wikitude, and Magic Leap all offer powerful and unique features but come with a cost. Unity MARS extends the capabilities of Unity, focusing on creating responsive AR experiences, Wikitude excels in image recognition and location-based AR, while Magic Leap provides a unique approach to AR, offering spatial computing capabilities for an immersive experience. Microsoft's Mixed Reality Toolkit (MRTK) stands out as a free tool that supports HoloLens 2 and offers a variety of input systems, but its application is primarily tied to the Windows platform.

For educators interested in employing AR, understanding its basic principles and educational applications is essential. While coding skills can be advantageous, many AR platforms offer user-friendly interfaces requiring little to no coding, making AR accessible for educators without programming experience [79]. Therefore, educators can meaningfully contribute to the digital transformation in education, despite not possessing extensive development skills [44].

4 AUGMENTED REALITY IN EDUCATION

The burgeoning digital era is driving transformative changes in all sectors, and education is no exception. As we move towards a more digitally-enhanced learning environment, Augmented Reality is emerging as a pioneering technology, altering the dynamics of traditional teaching methods and leading to the development of 'smarter' learning experiences.

4.1 A smarter learning experience through digital transformation in the digital era

AR, the technology that overlays digital information onto the physical world, provides an immersive, interactive, and engaging learning experience that significantly enhances educational outcomes [60,81]. By integrating AR into classrooms, teachers can deliver complex concepts in a more tangible and comprehensible manner, promoting active learning and fostering students' creativity and curiosity [81,82].

For instance, in science classes, AR applications can help students visualize complex biological processes or atomic structures. In history lessons, AR can bring historical events or figures to life, making learning more vivid and engaging. This interactive and immersive learning approach has been shown to increase student motivation, engagement, and retention [2,60,82]. Furthermore, the integration of AR into the educational curriculum isn't limited to the enhancement of teaching materials. It also extends to the transformation of physical learning environments. Classrooms are being redesigned with AR in mind, incorporating AR-enabled equipment and digital resources to support the adoption of this technology [83,86]. For instance, classrooms may be equipped with AR glasses or other AR-compatible devices, enabling students to interact with AR content seamlessly.

Despite the enormous potential of AR in education, its adoption isn't without challenges. It requires a considerable number of resources and technical skills to develop AR applications. Also, there's a need for teacher training to effectively integrate AR into their teaching practices [84]. However, the rapid advancements in AR development tools and platforms are making it increasingly feasible to overcome these obstacles. To illustrate, AR development platforms like ARCore, ARKit, and Vuforia, as discussed in Chapter 3, allow developers with basic programming skills to create engaging AR applications. Moreover, there are a growing number of ready-to-use AR educational apps available in app stores, which require no programming skills to use [2,85,86].

AR is revolutionizing the educational landscape by offering a 'smarter' learning experience. As we continue to navigate the digital era, the adoption and integration of AR in education will play a pivotal role in shaping future learning environments. While challenges persist, the benefits of AR in education are too promising to ignore [2]. Thus, more research and investment are needed to realize its full potential and to truly transform the learning experience in the digital age.

4.2 Enhance Learning by Adopting Augmented Reality in Classroom

The rapid advancement of digital technology has precipitated a seismic shift in pedagogical practices worldwide. Among these innovations, Augmented Reality (AR), the technology that superimposes digital content onto the real world, has emerged as a compelling tool in the realm of education [2,87]. Khan (2021) and O’Shea (2016) eloquently states that AR "allows students to see the unseen," effectively summarizing the transformative impact of AR on learning experiences [89,90].

Adopting AR in the classroom can significantly enhance student comprehension and retention. Its application in science classrooms is noteworthy. Students can visualize intricate biological processes or complicated physical systems in three dimensions, enabling a richer understanding of otherwise abstract concepts [88]. A case in point is a 2018 study conducted by Nechypurenko et. al, and 2017 study conducted by Akçayır & Akçayır, where students used an AR app to visualize molecular structures in chemistry classes, resulting in improved knowledge retention and comprehension [91].

The immersive nature of AR is another critical aspect, fostering increased student motivation and engagement [2]. According to a 2019 study by Khan, Johnson and Ophoff, AR-assisted lessons led to an enhanced sense of curiosity and interest among students, thereby improving academic performance [89]. In this light, AR appears not just as a teaching aid but as a catalyst for cultivating an active and inquisitive learning environment.

However, the adoption of AR in classrooms is not without its challenges. Foremost among these is the financial aspect. The cost of acquiring the necessary AR equipment and developing or sourcing suitable AR content can be substantial. This includes not only the AR devices and applications themselves but also the supportive digital infrastructure [76,84,87].

4.2.1 The importance and the ultimate goal

Augmented Reality's role in pedagogy is rapidly escalating as more educators realize the benefits of this transformative technology. The overlay of digital information on real-world elements brings an added dimension of realism and context that can significantly boost learning outcomes, something traditional teaching methods often fail to achieve [89,90].

The ultimate goal of integrating AR into teaching practices centers around three core aspects:

- enhancing comprehension,
- promoting engagement,
- and improving learning outcomes.

Each of these elements is crucial to the holistic development of learners in the digital age.

- Enhancing Comprehension: AR has demonstrated its potential to improve students' comprehension significantly. By providing a unique, interactive way to visualize complex concepts, AR can make learning more intuitive. Through AR applications, abstract concepts can be depicted in 3D models, enhancing the understanding and retention of knowledge. This capability is especially crucial in STEM education, where the complexity of subjects often presents a challenge [80]. A study by Akçayır & Akçayır (2017) in higher education found that AR applications significantly improved students' comprehension and academic success in complex subjects. They suggested that AR could make abstract concepts more concrete, thereby facilitating learning [91]. Similarly, in primary education, a study by Santos et al (2014) found that AR tools could improve students' understanding of natural science topics, especially those that are otherwise difficult to visualize [81].

- Promoting Engagement: AR's interactive nature promotes student engagement, turning learning into an exciting and immersive experience. By transforming passive learning into active engagement, AR increases student motivation and participation in learning activities [87,92]. D. Squires (2017), reported that the use of AR in higher education resulted in increased student engagement and motivation. Students were more likely to participate in class activities when AR tools were used [93]. In primary and secondary education, a study by M. Billinghurst, A. Clark, and G. Lee (2015) showed that AR can make learning more enjoyable, thereby promoting engagement. The interactive nature of AR fosters an active learning environment where students are eager to participate [60].
- Improving Learning Outcomes: Through enhancing comprehension and promoting engagement, AR naturally contributes to improved learning outcomes. Several studies have demonstrated the positive impact of AR on students' academic performance. In a study conducted by Wu, Lee, Chang, & Liang (2013), it was shown that AR instruction could enhance students' learning achievement in a higher education context [52]. Similarly, Radu (2014) and Z. Merchant et al (2014) highlighted that AR learning experiences could improve students' recall and retention capabilities, leading to better test scores [94,95]. Furthermore, AR has been found effective across various education levels even for middle school students [95].

4.2.2 The benefits of AR use in classroom

While AR revolutionizes learning by introducing interactive, immersive experiences from primary to higher education, there are many studies at all that AR offers tangible benefits that enrich the educational landscape, transforming traditional classrooms into dynamic learning environments. By summarizing the merits discussed in this thesis, we can highlight the following top ten benefits.

- Enhanced Comprehension: AR makes abstract concepts more tangible and easier to understand, facilitating better comprehension, especially in complex subjects like STEM.
- Increased Engagement: The interactive nature of AR transforms routine lessons into immersive experiences, leading to higher student engagement.
- Improved Learning Outcomes: Studies indicate that AR can boost academic performance, with students scoring higher on tests after learning through AR.
- Real-World Applications: AR provides practical, real-world examples, bridging the gap between theory and application.
- Personalized Learning: AR can be tailored to individual learning styles and paces, creating a more personalized education experience.
- Collaboration: AR encourages teamwork and cooperation among students, fostering a more collaborative learning environment.
- Accessibility: AR can bring distant concepts and places right into the classroom, making learning more accessible and inclusive.
- Motivation: The novelty and interactivity of AR can increase motivation and enthusiasm for learning among students.
- Skill Development: AR can aid in the development of essential 21st-century skills such as problem-solving, critical thinking, and digital literacy.
- Future-Ready: Exposure to AR technology prepares students for a future increasingly dominated by mixed reality and other advanced technologies.

4.2.3 The Challenges and Possible Pitfalls

Augmented Reality, while presenting numerous advantages in the educational landscape, is not devoid of obstacles when it comes to its integration into classrooms. These challenges span technological, pedagogical, and ethical facets, with certain hurdles being more prevalent at particular educational levels. The technological challenges encompass high cost of AR equipment, lack of technical proficiency, and the need for development of age-appropriate, curriculum-aligned AR content. The pedagogical concerns involve the necessary shift in traditional teaching methodologies and the potential disruption of classroom dynamics. Additionally, ethical and accessibility issues arise from privacy concerns and the potential for a widening digital divide. Recognizing and understanding these challenges are crucial steps in formulating effective strategies for AR integration, thereby maximizing its impact on education.

In the sections to follow, we delve deeper into each of these three broad categories of challenges, discussing their implications for learners ranging from primary to higher education levels.

4.2.3.1 Technological Challenges

AR implementation in educational settings presents a number of technological obstacles. One primary issue is the high cost of AR equipment. Especially for schools with limited resources, acquiring and maintaining AR devices can be prohibitive [96]. This challenge is prominent in primary and secondary schools, where budgets may be tighter compared to higher education institutions.

Another significant hurdle is the lack of technical proficiency among educators and students. To successfully operate AR technologies and troubleshoot problems, a certain level of technical knowledge is required. However, not all educators possess this expertise, and the same applies to students, especially in primary education [97].

Additionally, the development of effective AR content for educational purposes remains a challenge. While numerous AR applications exist, the lack of educational content that aligns with curriculum standards and is appropriate for different age groups and abilities can limit the utility of AR in the classroom [98].

4.2.3.2 Pedagogical Challenges

Beyond the technological hurdles, AR adoption in learning also presents pedagogical challenges. The integration of AR in teaching practices necessitates changes in the traditional pedagogical methods. Teachers need to be trained not only in using AR technology but also in modifying their instructional strategies to incorporate AR effectively [99].

Furthermore, the incorporation of AR could potentially disrupt the classroom dynamics. Over-reliance on AR technology might lead to decreased face-to-face interaction, which is crucial for students' social development, particularly in primary and secondary education [2,79,99].

The effectiveness of AR as a teaching tool also depends on its ability to engage students without overwhelming them. There is a risk that the novelty and excitement of AR might distract students from the learning objectives [100].

Moreover, assessment in AR-enhanced lessons presents a new challenge. Traditional assessment methods might not be suitable for AR-based lessons, necessitating the development of new assessment strategies [99,101].

4.2.3.3 Ethical and Accessibility Challenges

The use of AR in education also raises ethical and accessibility concerns. There are privacy and security issues related to data collection and storage, particularly when using AR apps that require access to personal information [102].

Furthermore, not all students have equal access to AR technologies, leading to a digital divide. Students in rural areas or disadvantaged communities might not have the same access to AR technologies as their counterparts in more affluent or urban areas [103].

While AR has great potential in education, these challenges highlight the need for strategic planning and thoughtful implementation. As AR technology evolves and becomes more accessible, these challenges might be mitigated, allowing more students to benefit from AR-enhanced learning experiences.

4.3 Use cases of using AR in classroom

Turning now to real use cases of using AR in classroom, this section explores how this emerging technology can create engaging and interactive learning experiences across a range of subjects. We'll delve into the impact of AR in Science, Technology, Engineering, and Mathematics (STEM) education, and its role in inspiring creative exploration in Arts and Humanities. The effectiveness of AR in supporting language acquisition will be scrutinized, highlighting its potential in fostering immersive, context-based learning. Finally, the unique benefits of AR in special education will be outlined, underscoring how customized AR experiences can empower students with special needs. Each section presents an overview of current applications and discusses recent research findings, offering a comprehensive picture of how AR is shaping the future of classroom learning.

4.3.1 Science, technology, engineering and mathematics (STEM)

AR has been used to augment the teaching of Science, Technology, Engineering, and Mathematics (STEM) subjects, offering a novel means of presenting complex concepts and processes. The interactive and immersive nature of AR facilitates hands-on learning and exploration, enhancing students' understanding and retention of STEM content.

Figure 23 - AR in School – Physics Class

For example, AR applications in biology could allow students to examine the anatomy of a human body (Figure 24) or the structure of a cell in three dimensions [104]. Similarly, physics students could manipulate 3D models of atoms or observe the forces in a simulated system or other 3D models that covered in lessons about volcanoes, which fall under the subject of Earth Science or Geology (Figure 23)

A 2018 study found that AR can significantly improve the learning outcomes in STEM subjects, suggesting a positive impact of AR on student motivation and engagement [105].

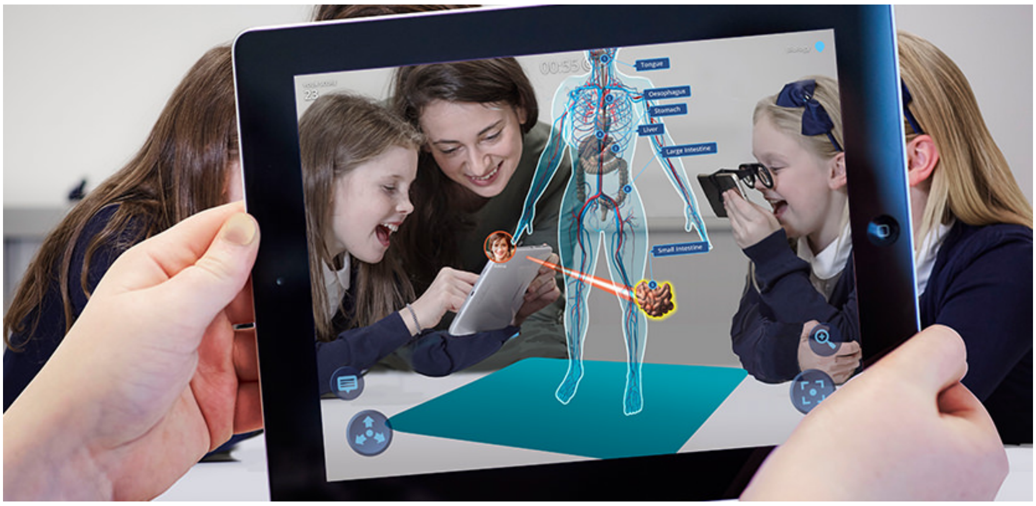

Figure 24 - AR in School – Biology Class

4.3.2 Arts and Humanities

In Arts and Humanities, AR offers unique opportunities for creative expression and exploration of historical and cultural contexts. In visual arts, AR applications can bring artworks to life, allowing students to explore the details and techniques used by the artist. In history classes, AR can provide an immersive exploration of historical events, sites, and artifacts, enhancing students' engagement and understanding (Figure 25).

Figure 25 - AR in School – History Class

A 2014 study indicated that AR can effectively enrich arts and humanities learning experiences, suggesting its potential for enhancing creativity and critical thinking skills [106,109].

4.3.3 Learning languages

AR provides valuable support for language learning by promoting interactive, context-based learning experiences. It can, for example, label objects in the real world with their names in the target language, facilitate role-playing scenarios, or display translations of written texts. This multi-modal and immersive approach to language learning can improve vocabulary acquisition, pronunciation, and communication skills. In a study conducted in 2018 and 2020, students using AR-based language learning applications showed increased motivation and improved learning outcomes [107,110].

4.3.4 Special education

AR can also be highly beneficial in special education settings, providing customized learning experiences that cater to the unique needs and abilities of students. For instance, AR can facilitate the learning of social skills for students with autism by simulating real-world social scenarios. Also, it can support students with physical disabilities by providing interactive learning experiences that bypass physical limitations. A 2016 and 2019 study found that AR technologies can contribute to the inclusivity of special education, helping students overcome learning barriers and enhance their self-esteem [108, 111].

4.4 Examples of successful AR applications in various educational environments

As presented in the previous section, AR applications are revolutionizing various academic disciplines, from STEM fields and humanities to language learning and special education. The versatility of this innovative technology is now motivating its adoption in the teaching plan, thus improving learning experiences and outcomes.

In light of this growing trend, the next section offers a detailed examination of specific cases of successful integration of AR applications in various educational environments. These include primary education, secondary education (K-12), and higher education levels.

4.4.1 Primary – Secondary / High School Education (K12)

Augmented reality (AR) applications have been successfully used in K-12 educational environments, enabling interactive and immersive learning experiences.

For instance, a comprehensive empirical study was conducted with 133 students, aged between 9 to 10 years, along with their teachers across five different schools located in London. The focus of this research was to draw a comparative analysis between conventional teaching methods and AR-infused pedagogical approaches regarding topics like earth, sun, and moon. In the feedback collected, the teachers acknowledged the potent role of AR in fostering learning, albeit with suggestions for a more flexible and customizable interface for AR applications, enabling the addition and removal of separate elements [115].

Furthermore, a case study conducted on a High School in Europe highlighted the effective utilization of the AR-based chemistry app, Elements 4D. The interactive nature of the application offered a real-time view of chemical reactions through the virtual combination of different elements. The outcome was an enhanced understanding of complex chemical concepts within a secure learning environment [112].

In a separate experimental study carried out in 2014, a total of 64 high school students were divided into experimental and control groups for learning basic principles of electromagnetism. Findings from this research indicated that AR-based applications were linked to a significant increase in academic performance, as well as fostering positive emotional experiences, when compared to traditional instructional methods in STEM fields. These findings underscore the potential of AR applications as effective educational tools, especially for high school electromagnetic courses [113].

Finally, an educational design research project employed Microsoft's HoloLens device in a secondary school setting in Australia. Both teachers and students reported a firm belief that the technology bolstered engagement and learning [114]. These varied case studies from schools across different regions contribute valuable evidence to the transformative potential of AR applications in

K-12 education, paving the way for more engaging and effective pedagogical methods.

4.4.2 Higher education

Augmented reality (AR) has emerged as a promising technology to help learn the structure and behavior of such artefacts, making it a valuable tool for engineering education (Figure 26).

Figure 26 - AR in School of Engineering - Analysis of virtual machine parts

AR also offers an alternative to traditional face-to-face engineering education, especially outside the classroom, allowing students to learn from home or in distance learning environments. In addition, AR is cost-effective and reduces occupational risks compared to physical laboratories. By implementing AR applications, universities can take advantage of economies of scale as each student can access a virtual lab using a tablet or smartphone. [116]

For instance, a 2018 study outlines a phased approach to the adoption of AR technology within the Power Engineering Faculty of the University Politechnica of Bucharest, Romania, providing students and educators with the necessary time to adapt to the shift, to recalibrate their perception of AR implementation, and to stay abreast of the latest technological advancements. Employing the freely available Aurasma platform, augmented information, visuals, and video content were generated to supplement textbooks, presentations, and experimental units across three laboratory settings.

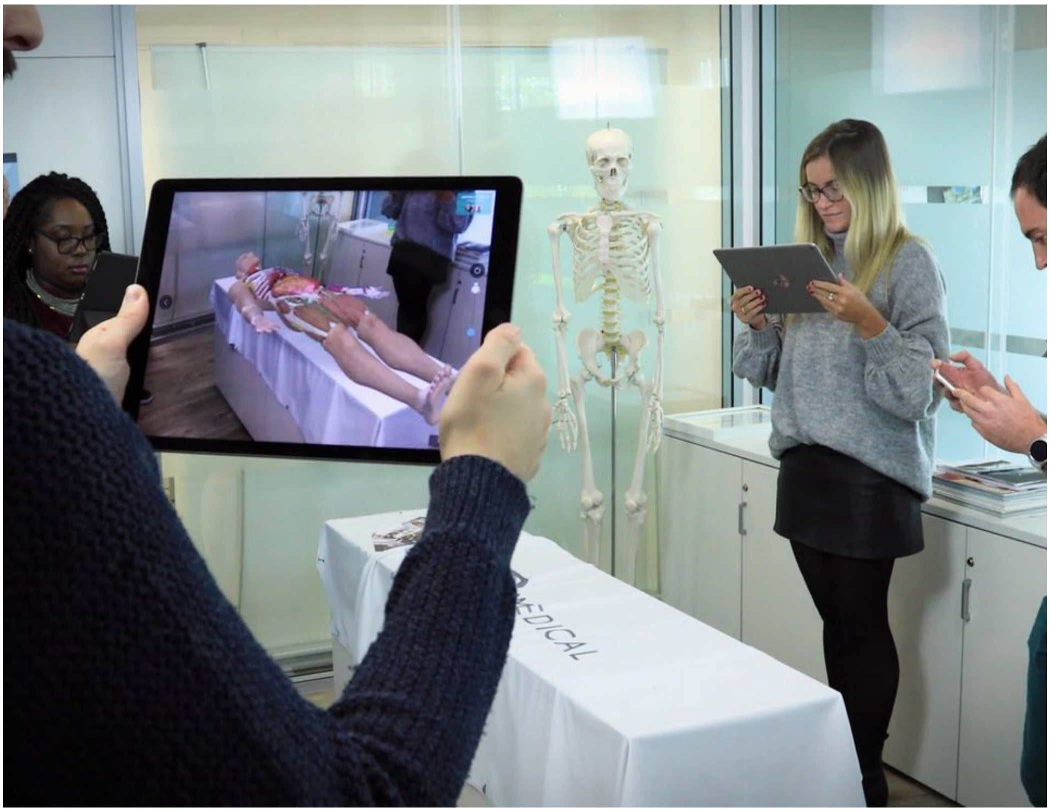

Figure 27 - AR in School of Medicine - A body of virtual patient

Another example regards medical education at the university level that involves assimilating extensive information about human anatomy and physiological functions (Figure 27). The advent of numerous digital tools, such as 'virtual cadavers,' has considerably facilitated this learning process [117]. Unlike traditional methods involving computer mice, keyboards, and screens, AR significantly enriches the manner in which medical students interact with digital anatomical models. By offering a comprehensive view from various angles, AR provides a more immersive learning experience that fundamentally boosts comprehension and retention of knowledge [118,119].

Figure 28 shows an example of the AR application, 'HoloHuman,' that displays a virtual cadaver superimposed on an actual examination table. A facilitator, equipped with a HoloLens headset, can manipulate the model and user interface. This technology allows for individual or combined examination of various anatomical structures, organs, and systems. Additionally, these visual explorations are enhanced by contextual narratives and digital dissection tools, thereby creating a comprehensive and interactive learning experience [118].

Figure 28 - AR in Medicine - App «HoloHuman» showing a virtual cadaver placed on a real examination table.

Understanding the relationship between anatomy and function is crucial in medical education, a comprehension facilitated by AR technology. AR allows for the simple addition or removal of anatomical elements like muscles or skeletal structures from the digital model [119]. Numerous AR anatomy applications feature functional elements, like the flexing of specific muscles to visualize the motion they govern. This is particularly useful for comprehending complex systems involving multiple muscle groups, such as ocular movement, enabling accessible learning at the student's convenience place. A case example comes by School of Medicine, Deakin University is the OculAR SIM AR program (Figure 29) to aid optometry students (available on multiple devices, such as tablets and smartphones, subject to licencing conditions) [119].

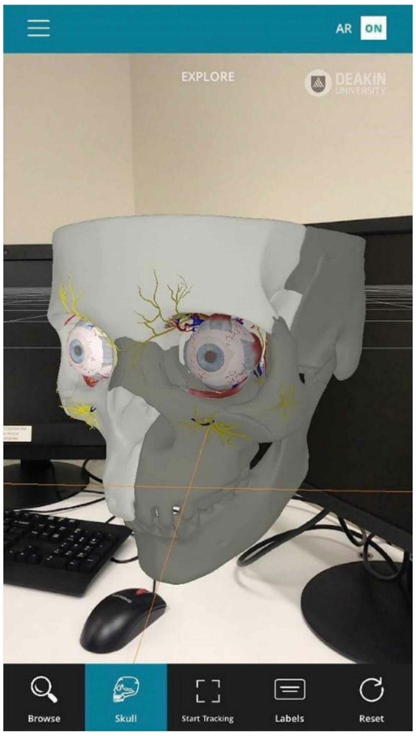

Figure 29 - AR use in Medicine - The OculAR SIM AR program to aid optometry students – Deakin University

Augmented Reality has shown its efficacy in enhancing learning in fields like engineering and medicine. In engineering, AR provides a safe, cost-effective method for understanding complex systems, as illustrated by its use at the University Politechnica of Bucharest, Romania [116]. For medical education, tools like 'virtual cadavers' and applications like 'HoloHuman' facilitate immersive anatomy studies [117, 118]. AR's capacity to demonstrate muscle movements, as shown by Deakin University's OculAR SIM AR program, highlights its benefits for understanding functional anatomy [119]. These instances collectively reflect the significant potential of AR in education.

By 2023, the educational landscape has been significantly transformed by the widespread use of augmented reality applications, most prominently on mobile devices. In other words, AR is everywhere (Figure 30). These applications span a diverse range of educational sectors and subject areas, from primary schooling through to higher education. In fact, AR has now become an integral part of many learning environments form primary to higher education.

Figure 30 - AR Everywhere - From Primary to Higher Education

The next section will explore various proven applications of Android-based augmented reality in education. These insights aim to equip educators with effective strategies for integrating this cutting-edge technology within classroom settings.

4.5 Tested AR Android-based applications for Education

Moving our discussion towards the realm of Android-based mobile AR applications in education, we embark on a journey to explore how this evolving technology serves as a dynamic tool for learning. The widespread accessibility and cost-effectiveness of Android devices, coupled with a multitude of free AR applications, present a promising platform for transforming educational practices. These applications not only offer unique features that promote interactive learning but also cover a broad range of educational topics.

From Mathematics and Science to Languages and Arts, Android-based AR applications span across various disciplines, offering immersive and engaging learning experiences. The versatility of Android's open-source operating system allows these applications to be highly customizable, catering to a variety of learning styles and educational objectives.

In this section, we present in a table the unique characteristics of some Android-based AR Mobile applications, the educational topics – teaching subjects they cover, supported languages and easiness of use according to Roussos et. al (2023) analysis [2].

This particular study is an application-focused exploration in which the researchers evaluated the stability of 40 Android Augmented Reality (AR) applications. The research was conducted in three phases, with the second phase representing the main experimental work. During this phase, the applications were tested on two different Android devices: a Xiaomi Mi 11 5G smartphone and a Samsung Galaxy Tab A8 tablet, both running Android 12 ("Snow Cone") [2]. The key criterion for the evaluation was the stability of the applications, i.e., their ability to run smoothly without "freezing" or "crashing" on either of the test devices. The results of this rigorous assessment led to the identification of 10 applications (highlighted in bold in Table 5) that successfully met the stability criteria on both devices [2]. Upon reviewing the data from the stability test of 40 Android AR-enabled applications, it is found that 10 applications successfully executed on both devices without any stability issues such as freezing or crashing. These applications include Anatomy AR, Arloopa, Assemblr Edu, Augment, Fectar, Google Arts & Culture, Halo AR, SkyView Lite, UniteAR, and Vuforia View [2, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131].

Application Name	**Device 1 Running**	**Device 1 Freezing/Crashing**	**Device 2 Running**	**Device 2 Freezing / Crashing**
Anatomy AR	**Success**	**No**	**Success**	**No**
Animal AR 3D Safari Flash Card	Success	Yes	Failure	Yes
Animal in Ar	Failure	Yes	Failure	Yes
Animal Safari AR	Success	No	Failure	No
AR Chemistry by Techax Labs	Success	Yes	Success	Yes
AR Elements	Success	No	Failure	No
AR Globe by Vivabro	Failure	Yes	Failure	Yes
AR Mongolia	Failure	Yes	Success	Yes
AR Pianist	Success	Yes	Failure	No
AR Scale - Measurements via AR	Success	Yes	Failure	Yes
AR Solar System	Success	No	Success	Yes
AR Studio Viewer	Success	Yes	Failure	Yes
AR Viewer	**Success**	**No**	**Success**	**No**
AR Voyage	Success	Yes	Success	Yes
AR Wilds	Success	Yes	Success	No
AR-3D Science	Success	Yes	Failure	No
Arloopa	**Success**	**No**	**Success**	**No**
AR-media - Augmented Reality	Success	Yes	Success	No
Aryzon AR Studio	Failure	Yes	Failure	Yes
Assemblr Edu	**Success**	**No**	**Success**	**No**
Assemblr Studio: Easy AR Maker	Success	Yes	Failure	Yes
Augment	**Success**	**No**	**Success**	**No**
Augmented Reality (AR) kid’s K	Success	No	Failure	No
Civilisations AR	Failure	Yes	Failure	Yes
Color Quest AR	Failure	No	Success	Yes
Craftland AR	Failure	Yes	Failure	Yes
DEVAR - Augmented Reality App	Success	No	Failure	No
DiFailuresaur 3D AR Augmented Reality	Success	Yes	Failure	Yes
Fectar	**Success**	**No**	**Success**	**No**
Google Arts & Culture	**Success**	**No**	**Success**	**No**
Halo AR	Success	No	Failure	No
LearnLive AR	Failure	Yes	Failure	Yes
Naddie AR	Success	Yes	Failure	Yes
Orboot Earth AR	Failure	Yes	Failure	Yes
Planets AR	Success	No	Success	Yes
Reality Maker - Build AR	Failure	Yes	Failure	Yes
ROAR Augmented Reality App	Failure	Yes	Success	Yes
SkyView Lite	**Success**	**No**	**Success**	**No**
UniteAR	**Success**	**No**	**Success**	**No**
Vuforia View	**Success**	**No**	**Success**	**No**

Table 5 - Examined 40 AR-based, Android Applications for educational purposes

Their successful operation on both test devices underscores their robust performance and stability, providing reliable AR experiences to users[4]. This suggests that these applications have been well-optimized for the Android platform, managing resources efficiently and handling potential errors effectively, consequently each one is a good choice for educational purposes [2].

The use of these AR applications in the classroom aligns with the ongoing digital transformation in education (Roussos et al., 2023). According to table (Table 6), reviewing the provided data related to the educational Android AR applications, several insights can be derived. The table illustrates that a range of applications exists, varying in user-friendliness, the diversity of topics covered, the ability to customize content, and compatibility with different Android versions.

Application	Android Version	Number of Topics	K12 Topics Covered	User Friendliness	Custom Content
Arloopa	8.0+	12	English, Math, Social Studies, Science, Fine Arts, Computer	Easy	Yes
Fectar	7.0+	8	English, Math, Social Studies, Science, Fine Arts, Computer	Medium	No
UniteAR	7.0+	1	English, Math, Social Studies, Science, Fine Arts, Computer	Easy	No
AR Viewer	9.0+	1	Science, Social Studies, Fine Arts	Hard	Yes
Augment	7.0+	1	Science, Social Studies, Fine Arts	Medium	No
SkyView Lite	6.0+	1	Science	Easy	No
Assemblr EDU	7.1+	8	English, Math, Social Studies, Science, Fine Arts, Computer	Easy	Yes
Vuforia View	8.0+	1	Science	Hard	Yes
Anatomy AR	4.4+	1	Science	Hard	No
Google Arts & Culture	5.0+	100+	Science, Social Studies, Fine Arts	Medium	Yes

Table 6 - Overview of Selected (10) Android AR Applications for Education

Arloopa, Fectar, and Assemblr EDU cover a broad array of K-12 topics including English, Math, Social Studies, Science, Fine Arts, and Computer, making them potentially more versatile for different educational contexts. Arloopa and Assemblr EDU also have the added advantage of allowing custom content, offering teachers the flexibility to tailor the learning experience to their students' specific needs [2, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131]. Applications like SkyView Lite, Vuforia View, and Anatomy AR focus primarily

[4] Educators / Students etc.

on science, which can make them useful for science classrooms looking to incorporate AR technology (Figure 31). These apps can bring scientific concepts to life, aiding in students' understanding and retention [2].

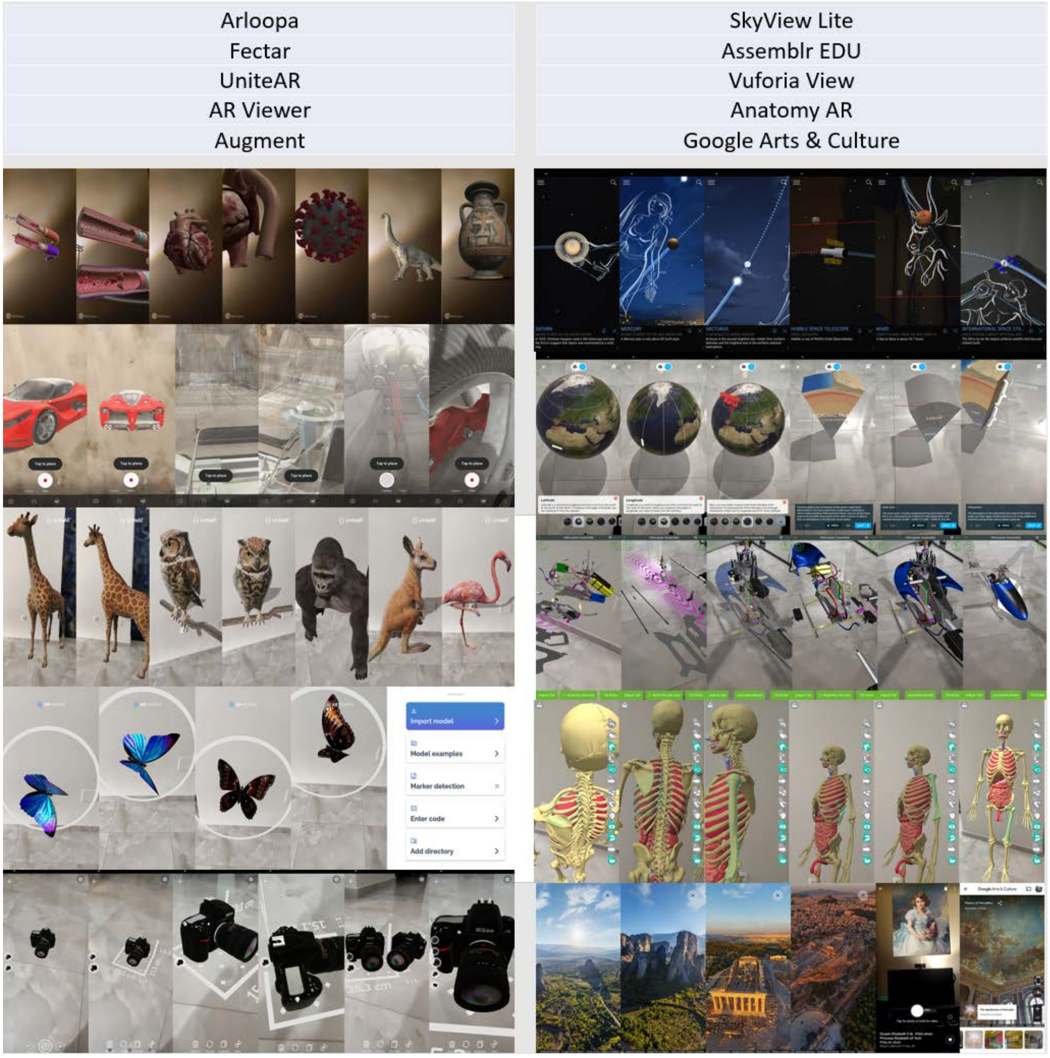

Figure 31 - Screenshots from 10 Selected Android AR Applications for Education

User-friendliness is another essential consideration. Arloopa, UniteAR, SkyView Lite, and Assemblr EDU are rated as 'Easy' in terms of user friendliness, suggesting that they might be easier for students to use and navigate, thus reducing the learning curve associated with new technology [2].

Google Arts & Culture stands out in terms of the sheer number of topics it covers, providing a wealth of material for educators to draw upon. Moreover, it allows for custom content, which can be a valuable tool for educators looking to customize their teaching materials [2].

The use of these AR applications in the classroom aligns with the ongoing digital transformation in education, empowering educators with innovative tools to engage students and enhance learning outcomes. AR technology provides immersive, interactive experiences, making learning more exciting and memorable for students [2]. These apps can help visualize complex concepts, stimulate curiosity, encourage exploration, and facilitate a deeper understanding, making them potent tools in the modern educator's arsenal [2,15]. The selection of appropriate AR applications depends on the specific needs, preferences, and context of each educational situation. Therefore, it's recommended that educators thoroughly explore and test these applications before integrating them into their teaching practice [14,15,19,23].

The upcoming section will present how teaching and technical staff at schools can draw upon creative strategies for designing an augmented reality-based digital classroom.

4.6 Innovative AR Implementation Strategies in the Classroom for the Digital Transformation Era

The last section of this chapter will discuss about the AR implementation and adoption strategies in classroom. More specific, this discussion will aim to suggest to educators and technical personnel with effective methods for integrating AR into the learning environment, thereby transforming the conventional classroom into an interactive and immersive AR-enabled digital classroom.

4.6.1 Technical Study

The initial step towards the adoption of Augmented Reality in an educational environment requires a comprehensive technical analysis. This phase involves understanding the necessary hardware, compatible software components and device requirements to facilitate effective integration of AR. Such a methodical exploration entails examining various AR platforms, devices and applications, thus selecting those that are compatible with the educational objectives, available resources and current technological infrastructure [15,88,120].

Moreover, exploring different approaches to instructional design, pedagogical strategies and monitoring methods enhances the potential of AR technologies for learning. Through such an evaluation, which includes aspects such as network connectivity and processing power, educators can make well-informed decisions about appropriate AR tools and strategies, thus ensuring the smooth and productive integration of AR technologies into their pedagogical practices and learning environments [91,120].

Designing an AR-compatible classroom requires meticulous planning of the layout. This includes careful consideration of device placement, accessibility to power sources, and ensuring ample space for students to interact with AR experiences [89,90,120]. In addition, the spatial layout should facilitate collaboration and allow for seamless transitions between physical and digital spaces. Furthermore, practical floor plans should accommodate diverse learning modes and meet the needs of all learners, thus promoting an inclusive learning environment [120].

Choosing the appropriate hardware and software for implementing AP requires a comparative study of different AP tools to identify the most appropriate for the educational needs and available resources. In addition, the continuous developments in AR technology necessitate awareness of emerging AR tools and platforms, helping educators to make informed decisions about the best hardware and software choices for their classrooms, leading to more effective and engaging learning experiences for students [120].

4.6.1 AR Implementation scenarios in Classroom

This section explores two scenarios for the implementation of Augmented Reality (AR) in classroom settings, from simple to advanced [120].

4.6.1.1 A' Scenario (simple)

A 2023 study by Roussos et al. [120], highlights the importance of meticulous planning and strategic arrangement when introducing Augmented Reality (AR) in a medium-sized classroom, aiming to accommodate 30-36 students. The emphasis is on the judicious use of available space and strategically placed equipment to optimize the AR learning experience (Figure 32). The authors recommend a robust Wi-Fi access point for seamless connectivity to all AR devices, along with secure, private wireless networks to protect sensitive data. They recommend providing teachers with laptops and smart devices for effective lesson planning, content delivery, and classroom management [120].

The authors further stress the importance of promoting an interactive and collaborative learning environment. To this end, they suggest the use of an ultra-short-throw projector to project high quality visual images with minimal shadows or blurring. They also recommend a wired PTZ 4K Ethernet camera to record classroom activities, facilitating distance learning and inclusive education. In particular, the authors argue that wired Ethernet connections offer increased security and stability, as well as superior data transmission capabilities, which is vital to maintaining the quality of the 4K video content being recorded. In addition, the authors suggest that wired systems may offer a more cost-effective option for educational institutions operating under budgetary constraints (Figure 32) [120].

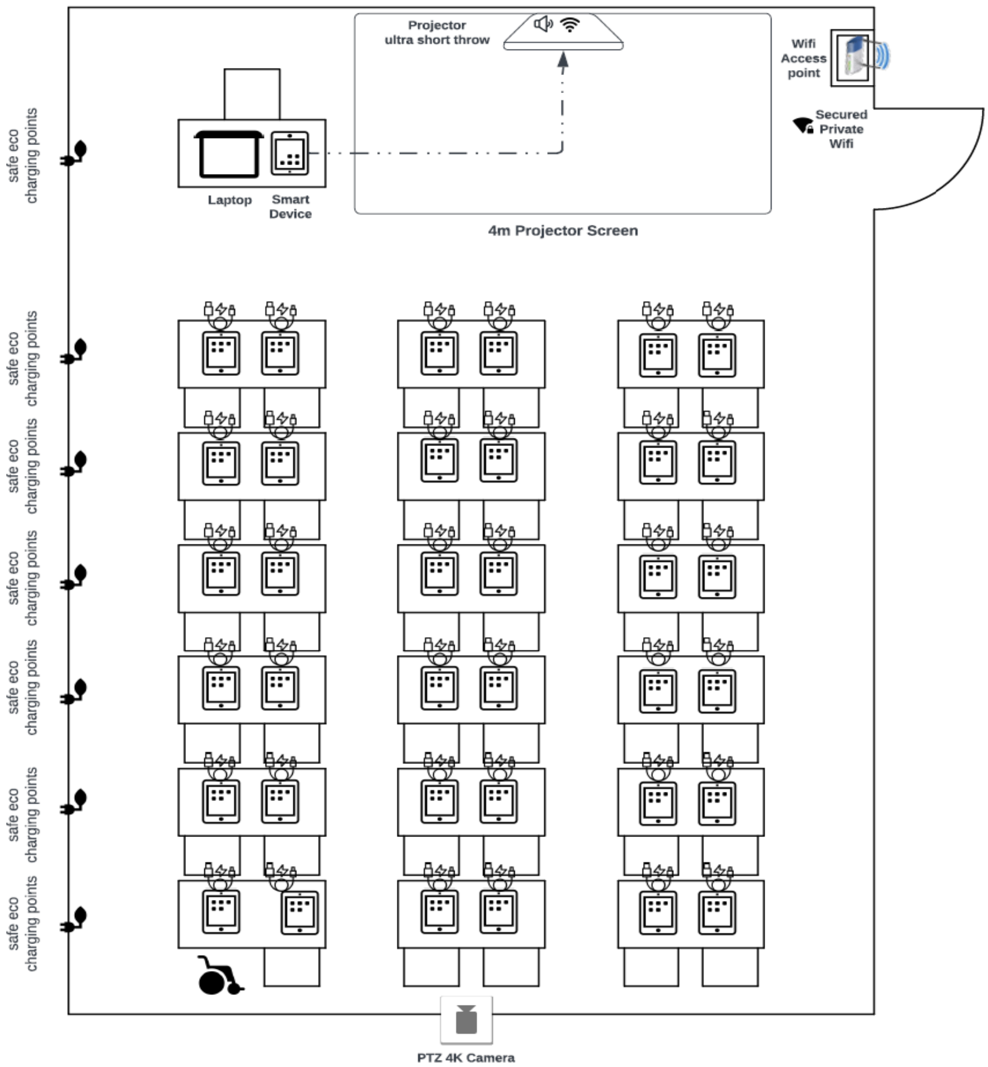

Figure 32 - AR Enabled Classroom - Simple Scenario - Floor Plan

Finally, the authors advocate for designing inclusive classroom layouts that take into account students with disabilities. They advocate providing adjustable desks, wide corridors for mobility, and designated spaces near the front or back of the classroom for better visibility and access to learning resources. The study concludes that careful integration of these elements can lead to the creation of an attractive, accessible, and technologically advanced classroom that maximizes the benefits of AR technology and promotes a collaborative learning experience for all students [120].

4.6.1.2 B’ Scenario (advanced)

In the same 2023 study by Roussos et al., the authors propose an advanced Augmented Reality (AR) enabled classroom layout that supports the pedagogical shift towards technology-enhanced learning. This cutting-edge design, accommodates 32 students and integrates sophisticated AR capabilities, whilst demonstrating a careful balance of technology and traditional classroom structure. It extends beyond mere Wi-Fi connectivity and entails thoughtful planning to effectively accommodate both technological and human elements [120].

The classroom is structured into four distinct sections, each accommodating eight students, with accessible provisions for students with disabilities (Figure 33). The inclusion of smart devices, such as iPads, and AI-equipped classroom elements like AI speakers and IoT smart lighting systems, facilitates interactivity and optimizes environmental conditions. The layout also features a 360-degree LED Holographic 3D display at the center, enabling students to engage with AR content from any vantage point, thereby enhancing the learning experience [120].

Complementing these student-centric elements, the classroom infrastructure also considers the needs of the educators. A strategically placed teacher's desk with a laptop and other smart devices aids in monitoring and guidance. The integration of a 4K interactive monitor with an AI 4K camera bolsters remote learning capabilities, acknowledging the emerging trend of hybrid learning environments. While the implementation of such an advanced AR-integrated classroom incurs significant initial costs, Roussos et al., highlight the long-term benefits that such technology-infused learning spaces offer. They emphasize the value of the immersive and interactive environment that these technologies create, which caters to the individualized learning needs of students. Although the financial commitment is substantial, the authors argue that this investment can lead to improved student outcomes, increased teacher effectiveness, and overall, a higher quality of education [120].

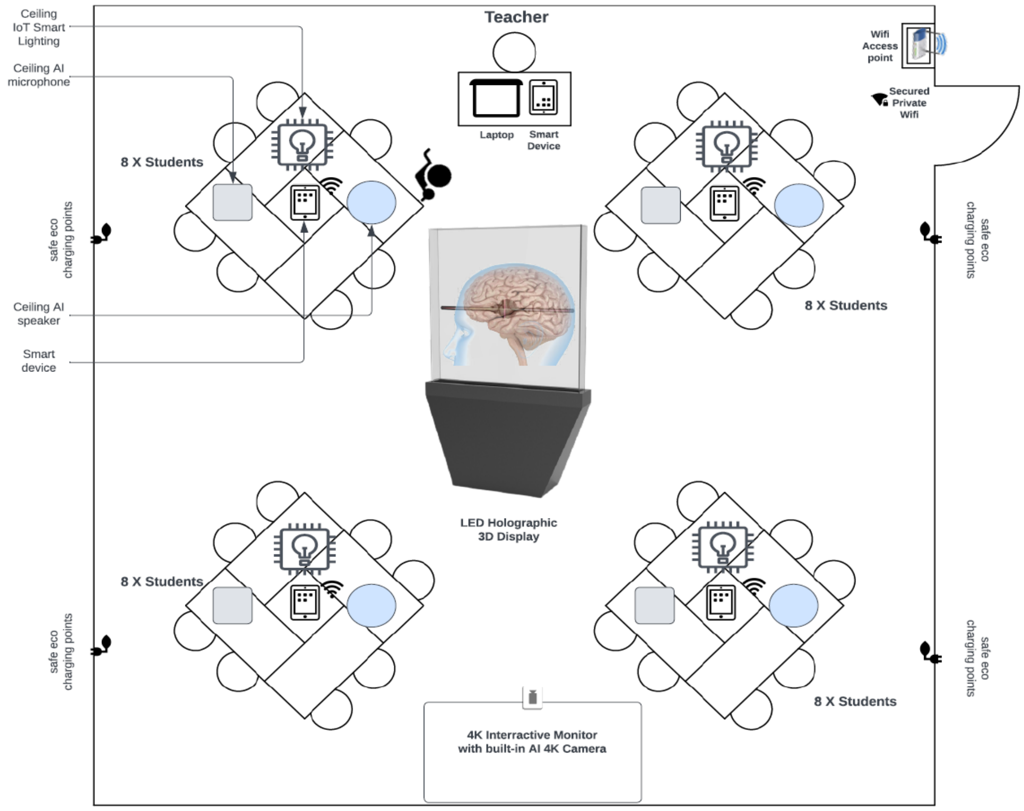

Figure 33 - AR Enabled Classroom – Advanced Scenario - Floor Plan

In conclusion, Roussos et al. underscore the transformative potential of AR in education. Through a proposed model of an advanced AR-enabled classroom, they demonstrate how judicious planning and integration of innovative technology can foster an immersive, engaging, and inclusive learning environment. Despite the initial costs, they posit that the long-term educational benefits and the increasingly accessible nature of technology make such investments not only feasible but necessary for the future of education [120].

4.6.2 Challenges and barriers to the adoption of AR in education

Despite the promising potential of Augmented Reality in transforming the educational landscape, several challenges and barriers still impede its wide-scale adoption. These hurdles stem from various domains, including technical constraints, cost and accessibility issues, resistance to change, and privacy and data security concerns.

4.6.2.1 Technical limitations

One primary concern is the technical limitations associated with AR technology. The effectiveness of AR in classrooms largely relies on robust infrastructure, including hardware capabilities, software compatibility, network connectivity, and processing power. These technical elements require extensive evaluation and testing to ensure seamless and efficient operation [2,120]. Moreover, the need for specific hardware and software could limit the use of AR technology, as these elements may not always be universally compatible with the diverse range of devices students use. Educators and institutions also need to consider the technical prowess of users as well as their capacity to navigate any technical hitches that may arise during the use of AR technology [60,65,79,].

4.6.2.2 Cost and accessibility

Another significant barrier is the cost and accessibility of AR technology. Notwithstanding the decreasing cost of technological devices over time, procuring the required hardware, software, and support systems to implement AR technology in classrooms can be quite substantial [42,44]. Furthermore, this financial burden may not be evenly distributed, leading to a widening digital divide between economically advantaged and disadvantaged students and institutions. Accessibility also extends to students with disabilities, making it essential to consider how AR technology can be made usable for all learners [80,82,90].

4.6.2.3 Resistance to change

In addition, resistance to change presents a substantial hurdle in adopting AR technology in education. Technological integration requires significant shifts in teaching and learning methodologies, which may be met with hesitation or resistance from both educators and learners [120]. Professional development programs for educators can help overcome this barrier by providing the necessary skills and knowledge for implementing AR in the classroom.

4.6.2.4 Privacy and data security concerns

Finally, privacy and data security concerns must also be addressed. With the surge in technology use in classrooms, safeguarding students' privacy and securing their data becomes paramount. Schools must adhere to strict privacy policies and take measures to protect sensitive student data to gain the trust of students, parents, and educators alike [16,42,44,60,120].

In conclusion, while the benefits of AR in education are numerous, it is essential to recognize and address these challenges and barriers to ensure a successful and inclusive implementation. A multi-pronged approach encompassing technical guidance, financial planning, pedagogical training, and robust privacy measures can pave the way for the successful integration of AR technology in classrooms.

5 CONCLUSIONS

In this study, we explored the role of digital transformation in education and specifically focused on the adoption of augmented reality (AR) in the classroom. By addressing the research questions outlined, we have gained valuable insights into the impact and potential of AR in enhancing learning experiences.

RQ1: Our findings highlight that digital transformation is reshaping education by integrating technology into various aspects of the learning process. Key elements of digital transformation in education include the use of digital tools, platforms, and resources, the shift towards personalized and interactive learning experiences, and the emphasis on collaboration and connectivity.

RQ2: We examined the unique properties, advantages, and limitations of AR compared to virtual reality (VR) and mixed reality (MR). AR stands out for its ability to overlay virtual content onto the real world, creating an immersive and interactive learning environment. This distinction influences the choice of technology in education, as AR provides a more accessible and user-friendly experience while still offering engaging and educational opportunities.

RQ3: Our research identified a range of AR tools and applications specifically designed for educational purposes. These applications encompass various subjects and offer features tailored to enhance learning, such as interactive simulations, 3D visualizations, and gamification elements. Understanding the primary characteristics and requirements of these AR tools is crucial for successful implementation in educational settings.

RQ4: The benefits of AR in classroom learning were demonstrated through successful examples from various educational contexts. AR has been shown to improve student engagement, understanding, and retention of knowledge. Effective implementation of AR in classrooms involves thoughtful curriculum integration, teacher training, and the use of pedagogically sound AR experiences that align with learning objectives.

RQ5: Converting a traditional classroom to a digital classroom with AR requires careful consideration of infrastructure requirements. This includes ensuring reliable internet connectivity, access to appropriate devices (such as smartphones or tablets), and creating a conducive digital environment for AR experiences. The paper talked about 2 implementation scenarios that could be adopted by teachers and relevant stakeholders in order to put into practice in the daily teaching of student learners. Collaboration between teachers, IT departments and policy makers is essential to address these infrastructure changes.

RQ6: Incorporating AR into classrooms presents challenges related to technical aspects, costs, and user adoption. Technical challenges involve the development of robust AR applications, compatibility with different devices, and overcoming potential technical limitations. Addressing cost concerns requires exploring cost-effective options and leveraging existing resources. User adoption issues can be mitigated through teacher professional development programs, creating a supportive and innovative culture, and involving students in the design and implementation process.

Undoubtedly, AR offers a transformative edge in education by fostering immersive learning environments. Capitalizing on its benefits demands embracing digital evolution, bolstering infrastructure, nurturing professional growth, and fostering collaboration in educational institutions. The resultant digital classrooms amplify learning outcomes and ready students for a rapidly digitizing world. As AR becomes increasingly ubiquitous, it affirms our emerging adage: "Augmented reality, everywhere!".

We do not know how far we are from this future moment, but we can proactively prepare ourselves (Figure 34, Figure 35, Figure 36, Figure 37).

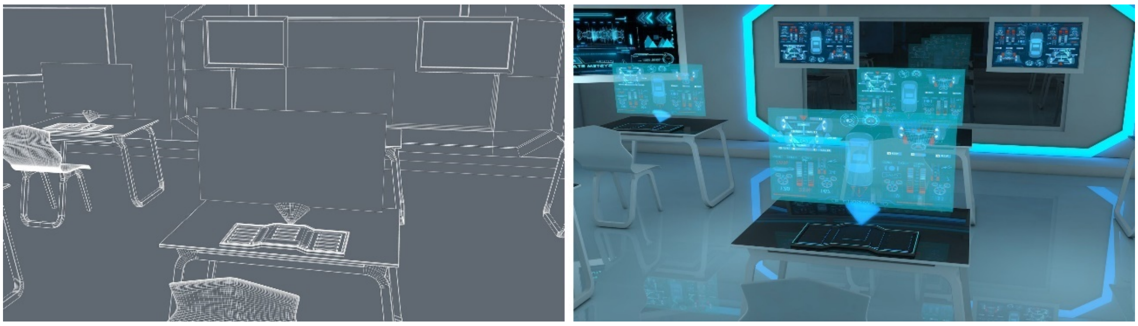

Figure 34 - 3D model of future classroom - view 1

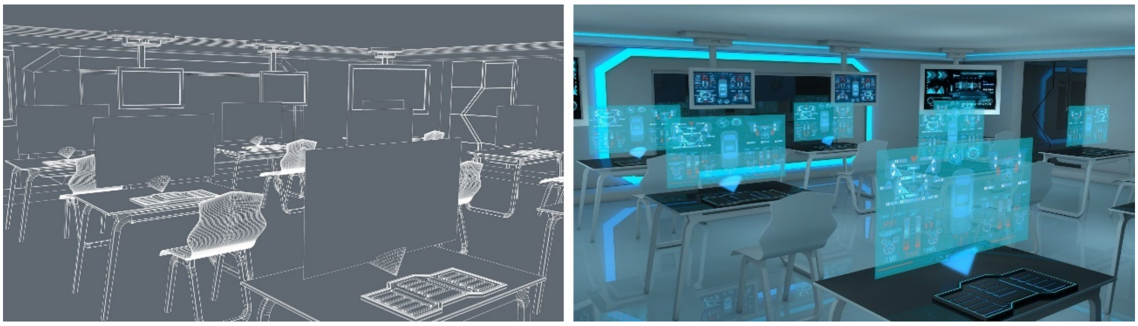

Figure 35 - 3D model of future classroom - view 2

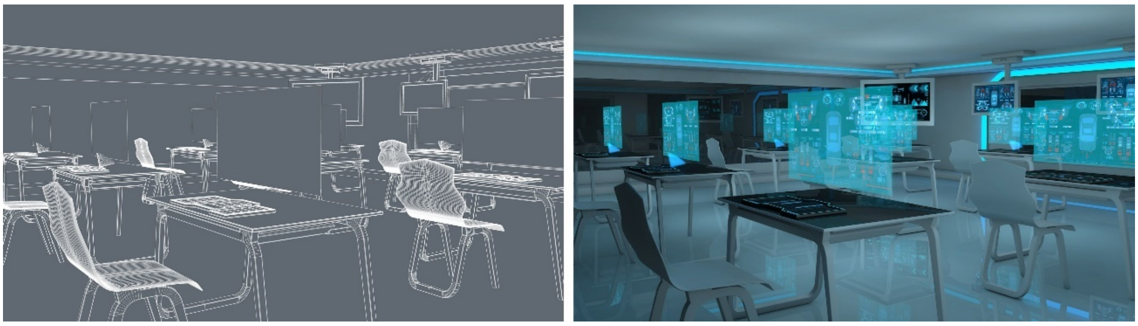

Figure 36 - 3D model of future classroom - view 3

Figure 37 - 3D model of future classroom in a smart city.

6
FUTURE RESEARCH

While this study provides valuable insights into the integration of AR in education, there are several areas that warrant further exploration. Future research should focus on emerging trends in AR and education, the potential of artificial intelligence AI and ML in improving AR experiences, the collaboration between AR and other emerging technologies in education, and recommendations for educational institutions considering AR adoption.

6.1 Emerging Trends in AR and Education:

As technology continues to advance, it is crucial to stay updated on emerging trends in AR and their implications for education. Future research should explore the latest developments in AR hardware and software, as well as innovative applications and pedagogical approaches. Understanding these emerging trends will help educators and policymakers make informed decisions about integrating AR into educational settings.

6.2 AI and ML in Improving AR Experiences:

AI and ML have the potential to enhance AR experiences by enabling personalized and adaptive learning. Future research should investigate how AI algorithms can analyze learner data, provide real-time feedback, and optimize AR content based on individual needs and preferences. Additionally, exploring the integration of AI-powered natural language processing and computer vision techniques can further enhance the interactivity and responsiveness of AR educational applications.

6.3 Additional practical studies for AR Adoption in Educational Institutions:

To support educational institutions in adopting AR, future research should provide practical recommendations and guidelines. These recommendations can encompass various aspects, including infrastructure requirements, teacher professional development programs, curriculum integration strategies, and evaluation frameworks for assessing the effectiveness of AR implementations.

Such recommendations will assist educational institutions in making informed decisions and overcoming challenges associated with AR adoption.

In conclusion, future research in AR and education should explore emerging trends, investigate the potential of AI and ML, examine collaboration with other emerging technologies, and provide practical recommendations for educational institutions. By addressing these areas, we can further unlock the transformative potential of AR in enhancing teaching and learning experiences.

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