

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Extended Reality (XR) and Its Role in Medical Education: A Survey

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Resumo

À medida que as tecnologias de Realidade Estendida (XR) ganham relevância nos domínios da saúde e da educação, compreender como são percebidas pelos estudantes de Medicina é essencial para garantir uma implementação eficaz. Esta dissertação explora as percepções dos estudantes de medicina relativamente à XR no ensino médico, com o objetivo de avaliar a sua utilidade percebida, eficácia e possíveis barreiras à sua adoção. Assim, foi realizado um estudo transversal entre estudantes do curso de Medicina do ICBAS, recorrendo a um questionário que recolheu dados qualitativos. As respostas foram analisadas através de estatísticas descritivas e inferenciais, tendo sido gerada uma nuvem de palavras para sintetizar o feedback de perguntas abertas.

Os resultados revelaram uma percepção geralmente positiva do valor educativo da XR, especialmente em áreas que exigem raciocínio espacial, treino de procedimentos e simulação imersiva, como anatomia, cirurgia e medicina de emergência. No entanto, muitos estudantes revelaram desconhecimento quanto às diferentes modalidades de XR, tendo o contacto prévio ocorrido sobretudo em contextos informais, como jogos. As preferências demonstraram inclinação para aprendizagens práticas e experienciais, com maior aceitação da XR quando esta se encontra alinhada com os objetivos pedagógicos. As percepções variaram consoante o ano curricular: os estudantes dos primeiros anos focaram-se no reforço teórico, enquanto os estudantes mais avançados valorizaram o realismo clínico. A confiança foi mais elevada na utilização da XR para tarefas visuais e de simulação, embora persistam preocupações quanto à sua capacidade de apoiar competências interpessoais, como a comunicação e o trabalho em equipa. Estes padrões sugerem que a XR deve complementar, e não substituir, as experiências do mundo real, sendo a sua integração feita de forma inclusiva e adaptada às diversas necessidades de aprendizagem.

Com base nestes dados, o estudo sugere uma abordagem faseada para a implementação da XR, incluindo uma introdução precoce à literacia em XR, seguida de aplicações específicas por disciplina, alinhadas com a progressão formativa dos estudantes. Investigações futuras deverão incluir a perspetiva dos docentes e avaliar a aplicação da XR em contextos reais através de projetos-piloto, permitindo a melhoria contínua das estratégias curriculares com base em dados concretos. Ao alinhar as capacidades tecnológicas com as necessidades pedagógicas, a XR pode enriquecer significativamente o ensino médico e preparar os estudantes para ambientes clínicos cada vez mais digitais.

Palavras-chave: Realidade Estendida (XR), Educação Médica, Integração Curricular, Estudo Baseado em Inquérito

Abstract

As Extended Reality (XR) technologies gain traction in healthcare and education, understanding how they are perceived by medical students is essential to ensuring their effective implementation. This dissertation explores medical students' perceptions of XR in medical education, aiming to assess its perceived utility, effectiveness, and potential barriers to adoption. Thus, a cross-sectional survey was conducted among undergraduate medical students at ICBAS, using a survey to collect qualitative data. Responses were analyzed using descriptive and inferential statistics, while a word cloud was generated to synthesize open-ended feedback.

Findings revealed a generally positive perception of XR's educational value, especially in areas requiring spatial reasoning, procedural practice, and immersive simulation, such as anatomy, surgery, and emergency medicine. However, many students lacked a clear understanding of XR modalities, with prior exposure mainly limited to informal contexts like gaming. Preferences leaned toward hands-on, experiential learning, with greater acceptance when XR aligned with pedagogical goals. Perceptions varied by academic year: early-year students focused on theoretical reinforcement, while senior students prioritized clinical realism. Confidence was highest in XR's use for visual and simulation tasks, but concerns remained over its ability to support interpersonal skills such as communication and teamwork. These patterns suggest XR should enhance, not replace, real-world experiences, and its integration must be inclusive and responsive to diverse learning needs.

Based on these insights, the study suggests a phased approach to XR implementation, comprising of early introduction of XR literacy, followed by discipline-specific applications aligned with students' educational progression. Future research should extend to educators' perspectives and evaluate real-world XR deployments through pilot programs, enabling data-driven refinement of curricular strategies. By aligning technological capabilities with pedagogical needs, XR can meaningfully enhance medical education and prepare students for increasingly digital clinical environments.

Keywords: Extended Reality (XR), Medical Education, Curriculum Integration, Survey Analysis

UN Sustainable Development Goals

The United Nations (UN) Sustainable Development Goals supply a global framework to achieve a better and more sustainable future for all. They consist of 17 goals designed to address critical global challenges such as poverty, inequality, climate change, environmental degradation, peace, and justice.

Although this dissertation focuses on a specific topic within medical education, it aligns with broader sustainable development themes by encouraging the responsible integration of innovative technologies into higher education. By analyzing medical students' perceptions of Extended Reality (XR) in their education, this work supports ongoing discussions on how to improve education quality, encourage innovation, and strengthen healthcare workforce training.

The specific Sustainable Development Goals mentioned have the following names:

SDG 3 Ensure healthy lives and promote well-being for all at all ages;

SDG 4 Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all;

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

SDG	Target	Contribution	Performance Indicators and Metrics
3	3.c	Indirectly supports the development and training of the healthcare workforce by exploring educational methods that may enhance clinical preparedness.	Student perceptions of XR's relevance to clinical practice; interest in applying XR in future professional settings.
4	4.3	Supports equal access to innovative educational tools in tertiary education and encourages digital literacy among medical students.	Proportion of students reporting prior experience with XR; perceived usefulness and willingness to adopt XR tools.
	4.4	Contributes to developing technical skills relevant to future employment in healthcare and digitally enhanced medical training.	Self-assessed digital competence; frequency of XR use in learning scenarios.
9	9.5	Promotes awareness of emerging educational technologies and encourages innovation in teaching practices within medical education.	Number of XR technologies referenced; interest in broader institutional adoption.

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<Vânia Veloso>

*“A jack of all trades is a master of none,
though oftentimes better than a master of one.”*

William Shakespeare

Contents

1	Introduction	1
1.1	Context	1
1.2	Motivation	3
1.3	Objectives and Expected Outcomes	5
1.4	Document Planning	5
1.5	Dissertation Structure	6
2	Background	8
2.1	Medical Education	8
2.1.1	Preclinical Phase	8
2.1.2	Clinical Phase	10
2.2	Extended Reality (XR)	13
2.2.1	Augmented Reality (AR)	14
2.2.2	Mixed Reality (MR)	15
2.2.3	Virtual Reality (VR)	16
2.3	XR in Portuguese Medical Education	17
3	State of the Art	19
3.1	Research Process	19
3.2	XR in Theoretical Medical Curriculum	21
3.3	XR for Skill Development in Medical Training	23
3.4	Challenges of Integrating XR in Medical Education	28
4	Methodology	29
4.1	Research Design	29
4.2	Study Setting and Participants	30
4.3	Survey Adaptation and Pilot Testing	30
4.4	Ethical Considerations	30
4.5	Data Collection	31
4.6	Data Analysis	32
4.7	Limitations	32
5	Results	34
5.1	Sample and Demographics	34
5.2	XR Awareness and Prior Experience	35
5.3	Perceived Utility and Format Preferences	39
5.4	Opportunities and Challenges of XR in Medical Education	44
5.5	Attitudes Towards XR in Medical Education	46

5.6	Proposed XR Scenarios in Medical Education	51
6	Discussion	53
6.1	Comparison to Previous Research	53
6.1.1	Demographics and Previous VR/XR Experience	53
6.1.2	Integration of VR/XR into Medical Curricula	54
6.1.3	VR/XR Integration in Clinical Specialties	55
6.1.4	VR/XR Integration in Preclinical Specialties	56
6.1.5	Advantages of VR/XR	56
6.1.6	Disadvantages of VR/XR	57
6.1.7	Patient Interactions in VR/XR	58
6.1.8	Ideas for VR/XR-Scenarios	58
6.2	Findings' Interpretation and Educational Relevance	59
7	Conclusion and Future Work	63
7.1	Conclusion	63
7.2	Future Work	64
	References	65
A	State of The Art Summary Table	75
B	Survey	82
C	Survey's Information Brochure	89
D	Article Adaptation	90

List of Figures

1.1	Kolb's cycle of experiential learning. From [11].	2
1.2	Representation of global healthcare market size and CAGR for the time period of 2023-2033. Data from [19][20]. *Value for AR and VR. **Value for XR.	3
1.3	Gantt Chart illustrating task's timelines and important delivery dates.	6
2.1	XR technologies, including AR, MR, and VR. From [28].	13
2.2	AR application for medical education. From [32].	14
2.3	MR in the operating room. From [38].	15
2.4	Application of VR in medical education. From [45].	16
2.5	XR technologies at CUF's simulation center. a) Heartworks®; b) Bodyworks Eve®; c) GI-BRONCH Mentor™; d) Mentice®.	17
2.6	XR technologies at the simulation center of the FMUL. a) EndoVR™ and LapVR™; b) VIST® G5.	18
2.7	XR technologies at Hospital da Luz. a) Bodyworks Eve®; b) ScanTrainer; c) ANGIO Mentor.	18
3.1	Flow diagram illustrating literature research, exclusion process, and number of included studies in the literature review.	20
5.1	Demographic characteristics of the study's population.	34
5.2	Students' rate of familiarity with XR.	36
5.3	Self-reported awareness of XR's component technologies.	36
5.4	Reported ability to differentiate between AR, MR, and VR.	37
5.5	Reported XR experience and context of XR use.	38
5.6	Perceptions distribution on the successful integration of XR.	39
5.7	Preferred clinical disciplines for XR integration.	40
5.8	Student's preclinical disciplines choices for XR integration.	41
5.9	XR integration preferences in teaching and evaluation formats	42
5.10	Advantages of XR in medical education as reported by students.	44
5.11	Student's reported disadvantages of XR technologies.	45
5.12	Distribution of responses across survey items rated on a 5-point Likert scale. . . .	47
5.13	Frequency distribution of participant ratings on the likelihood that XR technologies will influence the future of medical education, measured on a 0 (Very Unlikely) to 10 (Very Likely) scale.	50
5.14	Word cloud illustrating key terms from participant suggestions for XR-based scenarios in medical education.	51
B.1	Adapted survey used in the study.	88

C.1	Brochure with information regarding the study.	89
D.1	Article adaptation of the current Master's dissertation.	98

List of Tables

2.1	Courses for the 1 st , 2 nd , and 3 rd year of medical education for ICBAS, FMUC, and FMUL.	9
2.2	Courses for the 4 th , 5 th , and 6 th year of medical education for ICBAS, FMUC, and FMUL.	11
5.1	Demographic's summary table.	35
5.2	Students' XR knowledge summary table.	37
5.3	XR prior experience summary table.	39
5.4	Useful integration of XR in medical education, clinical and preclinical specialties, and class and evaluation format preferences for XR integration, a summary table.	43
5.5	Distribution of responses related to XR advantages and disadvantages.	46
5.6	Distribution of participant's responses to each of Q16's subquestions.	47
5.7	Distribution of participant ratings on the likelihood that XR will influence the future of medical education (Q17, scale 0–10).	50
A.1	Table showcasing the main information from the articles included in Chapter 3.	75

List of Acronyms

XR	Extended Reality
AR	Augmented Reality
MR	Mixed Reality
VR	Virtual Reality
Covid-19	Coronavirus
CAGR	Compound Annual Growth Rate
ICBAS	Instituto de Ciências Biomédicas Abel Salazar
FMUC	Faculdade de Medicina da Universidade de Coimbra
FMUL	Faculdade de Medicina da Universidade de Lisboa
2D	Two-Dimensional
3D	Three-Dimensional
VRLE	Virtual Learning Environment
CBL	Case-Based Learning
U.Porto	Universidade do Porto
CHUdSA	Centro Hospitalar Universitário de Santo António
QR	Quick Response

Chapter 1

Introduction

The goal of this chapter is to introduce the key elements of this dissertation; it is organized into five sections. In Section 1.1, the context is presented by delineating the rapid evolution of digital technologies in education — with a focus on Extended Reality (XR) in medical training — and discussing its current applications and challenges. Section 1.2, highlights the market trends and the growing investment in XR technologies, emphasizing the need for their integration into medical curricula. Section 1.3 details the objectives and expected outcomes of this study, setting the stage for an investigation into medical students’ perceptions of XR and its educational impact. In Section 1.4, the document planning is explained, including the project’s timeline and the use of a Gantt chart to structure the various phases of the research. Finally, Section 1.5 provides an overview of the dissertation’s structure, outlining how the subsequent chapters build upon the introduction to present the theoretical background, state of the art, methodology, results, and concluding insights.

1.1 Context

Over the past decade, rapid advances in digital technologies have transformed several facets of education, with medical education appearing as one of the beneficiaries. Among these innovations, XR stands out as a particularly promising approach for improving teaching and learning experiences, as it provides interactive environments where users are able to engage with digital content in a way that feels natural and immersive [1]. XR is characterized as an umbrella term, encompassing all immersive technologies, with the most known being Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR), each offering varying degrees of immersion by mixing real and virtual elements [2]. In medical education particularly, these technologies provide an interactive and safe environment for students to engage in simulated clinical scenarios, explore complex anatomical structures, and practice procedural skills without inherent risks associated with real-life patient care.

The field of medicine is constantly evolving to meet global healthcare needs [3]. Thus, as knowledge expands, equipping students with the necessary skills to navigate inherently complex

clinical environments becomes more and more important, ultimately leading to a better healthcare system [4]. However, medical education has been rooted in traditional practices such as classroom lectures, cadaver dissections, and direct clinical apprenticeships. While these methods have long served as the foundation for medical curricula, they also present several limitations, for instance, clinical placements are often constrained by patient availability, ethical considerations, and the unpredictability of clinical encounters; this raises concerns regarding the preparedness of recent graduates [5]. The coronavirus (Covid-19) pandemic further exposed these challenges, as, during the height of the pandemic, lockdowns and social distancing measures forced many institutions to either suspend or drastically alter in-person teaching, clinical rotations, and laboratory sessions. This disruption not only restricted direct patient interactions, but also highlighted the urgent need for alternative, technology-driven methods [6], such as XR technologies [7], to ensure continuity in medical education.

Historically, the integration of simulation-type technologies into medical education began with a simple shift from stationary slides to more dynamic ones [8]. However, the arrival of computer-generated images and advanced sensor technologies have transformed simulation-based medical education. XR technologies build upon this legacy by not only replicating real clinical environments with high fidelity but also by adapting these said environments in real time to student's actions. This desired interactivity cultivates deeper engagement and allows students to experiment and learn from mistakes without the pending thought of potentially jeopardizing patient safety [9]. These immersive, hands-on experiences are reflective of experiential learning (Figure 1.1), a pedagogical approach where knowledge is acquired through active participation and reflection on doing, leading to deeper understanding [10]. This method has shown particular value in fields like medicine, where real-world application is key to master skills.

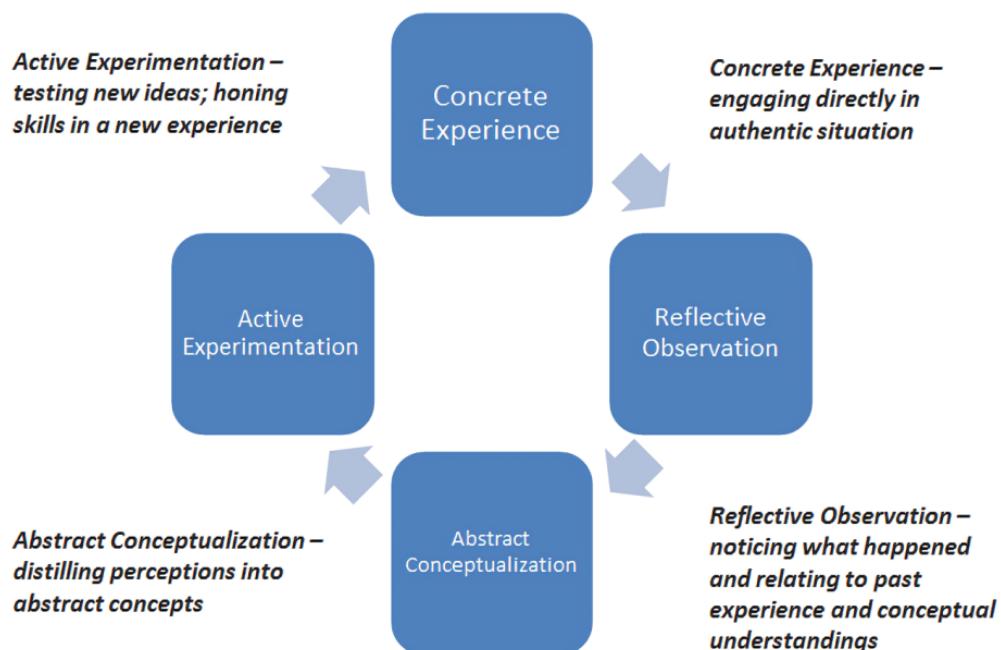


Figure 1.1: Kolb's cycle of experiential learning. From [11].

The benefits of XR go beyond the replication of real-life scenarios, since these technologies can also improve expandability, student engagement, and cost efficiency [12]. The varying degrees of the immersive nature of these technologies can improve cognitive engagement and facilitate the development of both psychomotor and decision-making skills. Studies in related fields have shown that learners who engage with immersive simulations often demonstrate improved retention rates and a more subtle understanding of complex concepts [13]–[17].

In the context of medical education, where the ability to quickly understand and act upon visual information can be critical, XR is offered as a powerful tool for perfecting diagnostic and surgical skills. Furthermore, XR’s potential to customize student’s learning experiences allows educators to alter simulations to accommodate specific objectives, thus supporting different learning styles and individual needs.

While the promise of XR in medical education is substantial, its integration into existing curricula is not without challenges. Factors such as high initial costs, the need for specialized technical support, or even the potential for technology-related distractions must be carefully considered [18]. In addition, the successful adoption of XR depends heavily on the student’s perceptions and readiness of educators. As institutions worldwide start and continue to invest in these technologies, understanding how medical students perceive and interact with XR becomes of high importance, since their insights can inform strategies that optimize user experience, ensure effective curriculum integration, and ultimately improve learning outcomes.

1.2 Motivation

The global healthcare market for AR and VR was evaluated at USD 3.4 billion in 2023 with an expected compound annual growth rate (CAGR) of 16.8% from 2024-2030 [19]. For XR, the global healthcare market stands evaluated at USD 7.8 billion in 2024, with an anticipated CAGR of 26.98% for the time period of 2025-2033 [20].

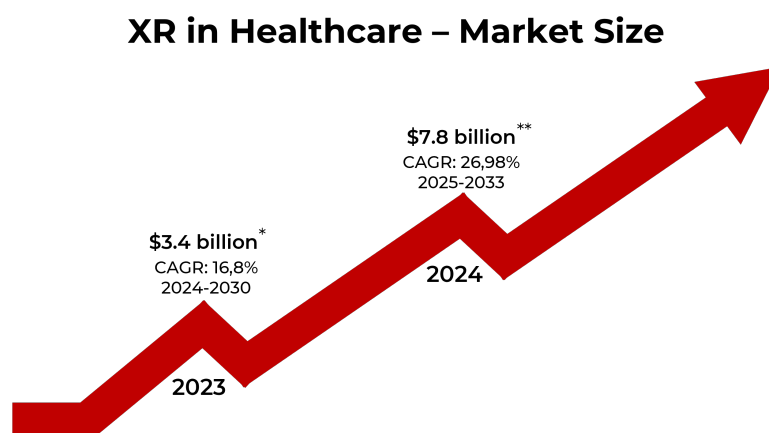


Figure 1.2: Representation of global healthcare market size and CAGR for the time period of 2023-2033. Data from [19][20]. *Value for AR and VR. **Value for XR.

This projection, as seen in Figure 1.2, makes apparent not only the rapid expansion and significant investment in immersive technologies within the healthcare sector, but also the need for extending these investments into medical education. As XR continues to evolve and integrate into clinical practice and training, it is important that educational institutions also invest in incorporating XR into their medical curricula. This possible integration will increase students' familiarity with these advanced tools, preparing them for a future in which such technologies are an integral part of healthcare. On the other hand, even if medical students end up not having to engage with XR in their professional careers, these technologies can still play a transformative role in their education. By utilizing XR's immersive and interactive features, as mentioned in Section 1.1, students can better visualize complex anatomical structures, simulate clinical procedures, and understand dynamic physiological processes that are often challenging to perceive through traditional teaching methods.

Moreover, early exposure to XR helps in cultivating an adaptable mindset, equipping future healthcare professionals with the ability to embrace and integrate emerging technologies throughout their careers. In this context, understanding student perceptions becomes of great importance. When students view XR as intuitive, engaging, and beneficial, it paves the way for smoother implementation and maximizes the educational potential of these tools. Conversely, negative perceptions can hinder adoption and reduce the effectiveness of XR-enhanced learning. Students' perceptions influence their willingness to engage with XR, and also how effectively they incorporate it into their academic careers. If students perceive XR as a practical tool that genuinely helps their understanding, then they are more likely to accept it into their study routines, actively participate in XR-based exercises, and develop a sense of confidence in using technology-driven learning aids. Otherwise, if they find it unintuitive, overwhelming, or misaligned with their educational needs, these technologies may be underutilized or even dismissed, leading to wasted resources and missed opportunities for improving medical education.

Furthermore, perceptions are shaped by several factors, including ease of use, perceived educational value, alignment with learning objectives, etc. Institutions must, therefore, not only provide XR tools but also ensure that they are tailored to student needs and expectations. Feedback from said students can uncover valuable insights into, for example, what types of content are most effective, and how educators can better integrate these technologies into their teaching methodologies. By prioritizing student perspectives, institutions can refine XR implementation strategies, making these tools not just an addition to the curriculum, but a fundamental asset in medical education. However, despite the increasing adoption of XR in medical education, there remains a significant gap in understanding how students perceive these technologies. Limited research has been conducted on their attitudes, concerns, and expectations regarding XR as a learning tool, leaving open the possibility for a failed or incomplete integration of these technologies into medical education.

1.3 Objectives and Expected Outcomes

Keeping in mind the increasing investment in XR technologies within healthcare and their potential in medical education, it is important to understand how students perceive their role in learning. While XR enables promising opportunities for enhanced medical training, its successful adoption is dependent on how well it aligns with the primary stakeholders - medical students - needs and expectations. By exploring these perceptions, this master's dissertation aims to bridge the gap between technological advancements and their practical implementation. To achieve this, the master's dissertation is guided by the following objectives:

- Assess the utility of XR technologies in medical education: Evaluate how medical students perceive the usefulness of XR in enhancing their learning experiences.
- Explore student perceptions of XR's effectiveness: Investigate how medical students feel about the integration of XR, focusing on engagement, ease of use, and educational value.
- Identify barriers to XR adoption: Understand the challenges students foresee or experience in the implementation of XR technologies within their curriculum.
- Support future developments in XR-assisted medical education: Provide data that can inform and guide the future integration of XR into medical teaching practices.

By achieving these objectives, this dissertation hopes to deliver valuable insights into how medical students perceive the integration of XR into their educational curriculum. Here, it is anticipated that students will generally recognize XR as a possibly beneficial tool that has the potential to enhance their learning experience, particularly in understanding complex medical concepts and improving hands-on skills through interactive simulations. However, despite this anticipated openness, students may also express reservations regarding this integration. Concerns may arise regarding fidelity, technical limitations, or even the learning curve associated with the adaptation to new technologies.

Ultimately, any and all findings hope to help educational institutions optimize XR integration into their medical curricula. By balancing technological potential with student expectations, the aim is to contribute to a more seamless adoption of XR in medical education, improving overall learning outcomes while addressing possible apprehensions.

1.4 Document Planning

This dissertation was planned keeping in mind important delivery dates. In doing so, a Gantt chart (Figure 1.3) was elaborated, thus providing a structured timeline, outlining the key phases necessary for the successful completion of this document.

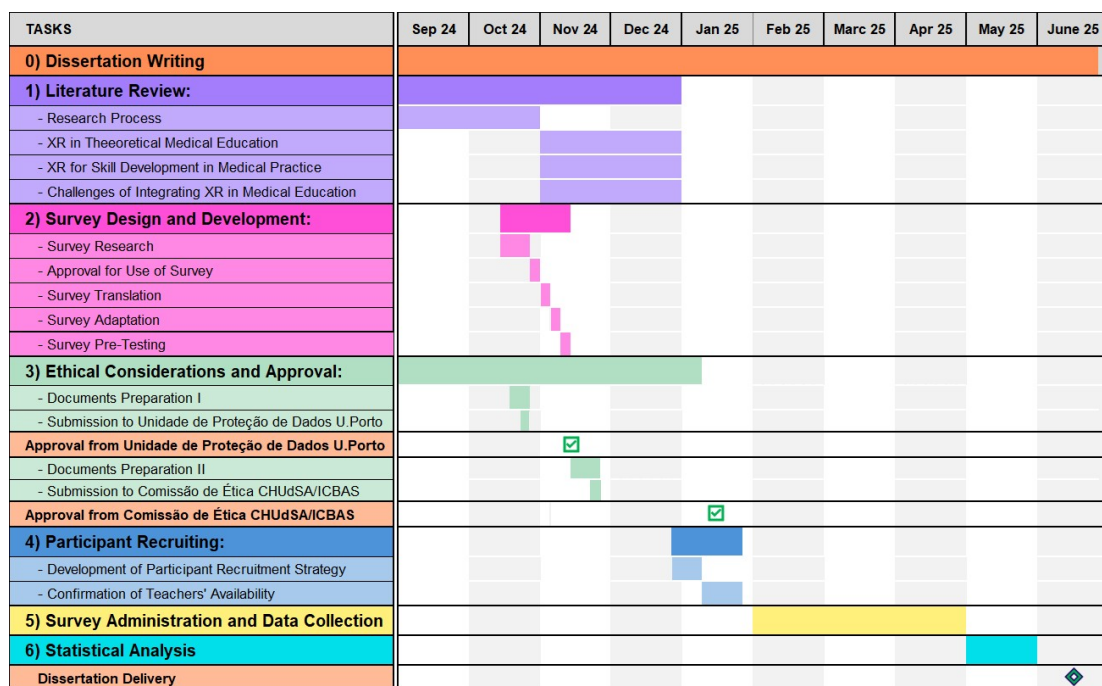


Figure 1.3: Gantt Chart illustrating task's timelines and important delivery dates.

The process began with the introduction phase, providing the initial gathering of knowledge to properly describe the context, motivation, objectives and expected outcomes, and document planning. Following this, the theoretical background phase was carried on to ensure that the necessary fundamental knowledge regarding medical education and XR was accurately understood, to serve as a base for the following phases. Then, to assess the current state of XR for medical education, the state of the art phase involved research on up to date scientific articles on the use of XR for the theoretical medical curricula, for skill development in medical training, and the main challenges faced when integrating XR into the medical curricula. Following this, comes the methodology phase, planning and describing what was done to assess medical students' perceptions on the use of XR in their education. Consequently, the results phase is presented to showcase the collected data, offering insight into students' perspectives on XR's educational value, engagement, and perceived challenges. This leads to the discussion phase, where the findings are analyzed in depth, compared to existing literature, and interpreted in the context of XR's role in medical education. Finally, the conclusion and future work phase summarizes the key takeaways of the study, reflecting on its contributions, limitations, and possible directions for further research and advancements in XR integration.

1.5 Dissertation Structure

In addition to the introduction, this dissertation contains 6 more chapters to provide a coherent narrative from context to conclusion. Following the introduction, Chapter 2 establishes the necessary background by exploring medical education, both its preclinical and clinical phases, and

introducing the fundamentals of XR, including its applications and current usage in Portuguese medical education. The following Chapter 3 reviews the state of the art, discussing the research process, the integration of XR into theoretical curricula, its role in skill development, and the challenges associated with its adoption. Subsequent Chapters 4, 5, and 6 detail the methodology used to assess medical students' perceptions, present the study's results, and discuss these findings in relation to existing literature. The document concludes with the final Chapter 7 that summarizes the contributions of the research and outlines directions for future work. Additionally, the appendices include a state of the art summary table (Appendix A), the survey used in the study (Appendix B), the survey's information brochure (Appendix C), and an article format adaptation of the dissertation intended for future publication (Appendix D).

Chapter 2

Background

This chapter provides an overview of the foundational areas supporting this study. It covers the structure and evolution of medical education (Section 2.1) with a particular focus on its two major phases: preclinical and clinical. In addition, the chapter introduces XR technologies in Section 2.2, including AR, MR, and VR, and discusses their emerging role in enhancing medical training, with a special focus on the Portuguese context (Section 2.3).

2.1 Medical Education

Medical education is characterized as the course of study designed to provide physicians the required knowledge and skills needed to prevent and treat diseases [21]. It not only transmits current scientific understanding but also encourages the development of research methods to investigate the many unknown factors that influence health and disease. At its core, medical education is about cultivating physicians who are responsive to the unique health needs of their communities while remaining adaptable as medical science evolves. The education of medical students is commonly divided into two phases: preclinical phase and clinical phase.

2.1.1 Preclinical Phase

The preclinical phase of medical education, as its name suggests, is a precedent to the clinical phase, serving as the fundamentals that will support it. During this stage, usually spanning over the first three to four years of college, students immerse themselves in a broad spectrum of scientific disciplines. Coursework aims to cover basic medical concepts, including the structure and function of the human body, the mechanisms underlying disease, and the principles of diagnosis and treatment. In addition to these scientific subjects, the curriculum introduces basics of doctoring, such as effective patient communication, history-taking, and other core clinical competences.

This phase is characterized by a blend of traditional classroom instruction and interactive laboratory work. Didactic lectures transmit detailed knowledge about anatomy, physiology, biochemistry, pathology and pharmacology [22]. Laboratories and simulation exercises complement these lectures by allowing students to explore anatomical models and experimental data, reinforcing theoretical concepts through practical observation.

Problem-based learning has also become has also gained room as a central element of the preclinical curriculum. Through problem-based learning, students work on clinical scenarios that require them to apply foundational scientific principles to real-world problems. This approach promotes analytical thinking and early diagnostic capability, decreasing the gap between theory and actual practice [23]. By working collaboratively on these case studies, learners develop the skills necessary for effective clinical decision-making, team working, and patient management later in their careers.

Nevertheless, the preclinical phase is not merely about acquiring a panoply of knowledge; it also aims to develop the capacity for continuous learning. Curricular designs are intentionally flexible, allowing adjustments as medical knowledge expands and health care needs evolve. Below, Table 2.1, can be seen demonstrating curricula for Instituto de Ciências Biomédicas Abel Salazar (ICBAS), Faculdade de Medicina da Universidade de Coimbra (FMUC), and Faculdade de Medicina da Universidade de Lisboa (FMUL), as an example of medical programs in Portugal.

Table 2.1: Courses for the 1st, 2nd, and 3rd year of medical education for ICBAS, FMUC, and FMUL.

ICBAS	FMUC	FMUL
1 st Year		
Systematic Anatomy I	Anatomy I	Introduction
Cell and Tissue Biology	Biochemistry I	Molecular, Cellular, and Human Development Biology and Genetics
Fundamentals of Chemistry and Biophysics	Cellular and Molecular Biology I	Organ Systems and Functions
Introduction to Medicine I	Introduction To Clinical Medical Practice I	Clinical Medicine: The Doctor, the Person, and the Patient
Quantitative Methods	Research Methods I	Ethics and Social Sciences
Biochemistry and Metabolism	Elective (x1)	Basic Life Support
Systems Histology and Embriology	Anatomy II	Molecular, Cellular, and Human Development Biology and Genetics
Basic Genetics	Biochemistry II	Organ Systems and Functions
Introduction to Medicine II	Cellular and Molecular Biology II	Clinical Medicine: The Doctor, the Person, and the Patient: - Nursing Care Internship - Community Health Practice I
Systematic Anatomy II	Histology and Biology of Development I	
	Introduction To Clinical Medical Practice I	
	Elective (x1)	

ICBAS	FMUC	FMUL
2 nd Year		
Molecular Genetics	Anatomy III	Organ Systems and Functions
Immunology	Genetics I	Microbiology / Immunology / Infectiology
Nervous System Anatomy and Physiology	Histology and Biology of Development II	Introduction to Women's Medicine
Physiology I	Immunology I	2 nd Year Elective Core
Epidemiology and Public Health	Introduction to Clinical Medical Practise III	Clinical Medicine: The Doctor as Person and the Patient/ Community Health Practice II
Psychology	Physiology I	Introduction to the Pathology of Organ Systems
First option (2 nd Academic Year/1 st Semester)	Research Methods II	Neurosciences
Pathology I	Genetics II	Introduction to Pediatric Medicine
Physiology II	Immunology II	Optional Curriculum Core of the 2 nd Year
Clinical Anatomy	Introduction to Clinical Medical Practice IV	
Microbiology	Methodology of Investigation /Health Population III	
Option 2 nd and 3 rd (2 nd year/2 nd semester)	Microbiology & Parasitology	
	Electives (x3)	

3 rd Year		
Radiological Semiotics	Anatomical Pathology I	Clinical Medicine: The Doctor, the Person, and the Patient
Semiology and Fisiopathology I	Ethics, Deontology and Professional Practice	Introduction to the Pathology of the Organ Systems
Pathology II	Pathophysiology	Imaging
Pharmacology I	Pharmacology I	Public Health/ Epidemiology/Genetics
Medical Microbiology	Propedeutics I	Introduction to Mental Health
Semiology and Fisiopathology II	Elective (x1)	Introduction to Diseases of Aging
Laboratorial Semiotics	Anatomical Pathology II	Optional Core Curriculum of the 3 rd Year
Medical Genetics	Medical Psychology	Oncobiology
Pharmacology II	Methodology of Investigation/ Population Health IV	Introduction to the Principles of Therapeutics
Medical Epidemiology	Pharmacology II	Clinical Medicine: The Doctor, the Person, and the Patient
Medical Psychology	Propedeutics II	Conditional Option (x1)
	Radiology	Imaging
	Elective (x1)	Optional Core Curriculum of the 3 rd Year

2.1.2 Clinical Phase

Transitioning from the mainly theoretical framework of the preclinical phase, the clinical phase focuses greatly on the practical application of medical knowledge through direct patient care. This stage of education is typically organized around clinical hands-on experience under the guidance of seasoned doctors.

During clinical rotations, students actively participate in patient care activities across disciplines such as internal medicine, surgery, pediatrics, psychiatry, obstetrics-gynecology, and others

[24]. They learn to perform medical histories and physical examinations, develop differential diagnoses, and put together treatment plans. This in-field experience is fundamental in transforming classroom knowledge into real-world clinical competence. A key component of the clinical phase is the emphasis on experiential learning through simulations and direct patient interactions. High-fidelity simulators and standardized patient encounters allow students to practice procedures and manage serious medical situations in a controlled, risk-free environment. These simulated experiences significantly improve both the learning process and clinical skills of healthcare professionals [25], which, when paired with reflective debriefing sessions, provide feedback on the students' performance, thus fostering continuous improvement in clinical skills and decision-making.

Beyond technical proficiency, the clinical phase also plays an important role in shaping professional identity, as, in a study by Findyartini *et al.* [26], the more senior students obtained a higher score on a professional identity formation questionnaire. By working alongside experienced doctors, students learn to navigate the intricacies of patient care while developing essential soft skills such as empathy, communication, teamwork, etc. The mentorship and guidance provided during clinical rotations help stimulate a sense of responsibility and ethical practice, both of which are vital for the formation of a competent and caring doctor. Furthermore, much like in Subsection 2.1.1, this phase reinforces the concept that medical education is an ongoing process. As students encounter diverse patient populations and varying clinical scenarios, they are encouraged to view each experience as an opportunity for continuous growth and learning. This mindset is essential for adapting to the ever-changing landscape of healthcare, where new challenges and innovations constantly emerge. Below, in Table 2.2, clinical curricula of the ICBAS, FMUC, and FMUL can be observed, continuing the previous example of Subsection 2.1.1.

Table 2.2: Courses for the 4th, 5th, and 6th year of medical education for ICBAS, FMUC, and FMUL.

ICBAS	FMUC	FMUL
4 th Year		
Surgical / Medical Group - 4 th Year	Dermatology	Medicine / Surgery
Fourth option (Medical Group - 4 th Academic Year)	Integrated Unit of Pathology and Medical Therapeutics	Elective Curriculum Core of the 4 th Year
Surgical / Medical Group - 4 th Year	Ophthalmology	Medicine / Surgery
Fourth option (Medical Group - 4 th Academic Year)	Otorhinolaryngology	General and Family Medicine
	Pathology of the Digestive System	Forensic Medicine
	Elective (x1)	Clinical Neurosciences and Psychiatry

ICBAS	FMUC	FMUL
4th Year		
	Curricular Unit of Endocrinology	Cross-professional skills: Evidence-based Medicine and Health Literacy, Health Systems and Costs in Medicine.
	Hematology	Elective Curriculum Core of the 4 th Year
	Legal and Forensic Medicine and Medical Law	
	Neurosciences and Mental Health	
	Oncology	
	Research Methods/ Population Health V	
	Elective (x1)	
5th Year		
Medical / Surgical Group - 5 th year	General and Family Medicine	Medicine / Surgery
Sixth option (6 th Academic Year - Medical Group)	Gynecology and Obstetrics	Elective Curriculum Core of the 5 th Year
Fifth option (5 th Academic Year - Surgical Group)	MIM Final Work Project	Medicine / Surgery
Medical / Surgical Group - 5 th year	Paediatrics I	Obstetrics and Gynecology
Sixth option (6 th Academic Year - Medical Group)	Thoracic and Vascular Pathology	Cross-Professional Skills: Communication with Patients and Families, Quality and Safety in Health Care, Professionalism, Medical Ethics.
Fifth option (5 th Academic Year - Surgical Group)	Elective (x1)	
	Infectious Diseases Unit	
	Musculo-Skeletal Conditions	
	Paediatrics II	
	Urinary Tract Pathology	
	Elective (x1)	
6th Year		
Dissertation/ Project/ Internship	MIM Final Work	Professional Clinical Internship
Mental Health	Programmed and Directed Mentored Stage	Final Project of the Integrated Master's in Medicine
Hospital Surgery		
General and Familiar Medicine II		
Woman's Medicine		
Hospital Medicine		
Medicine of Children and Adolescents II		

2.2 Extended Reality (XR)

As previously mentioned in Section 1.1, XR is an umbrella term for technologies that merge the physical and the digital, including AR, MR, and VR (Figure 2.1), which fuse the real and digital worlds in varying degrees. These technologies are often considered along a continuum of immersion, the Milgram and Kishino's reality-virtuality continuum, with XR serving as an inclusive term for this spectrum [27].

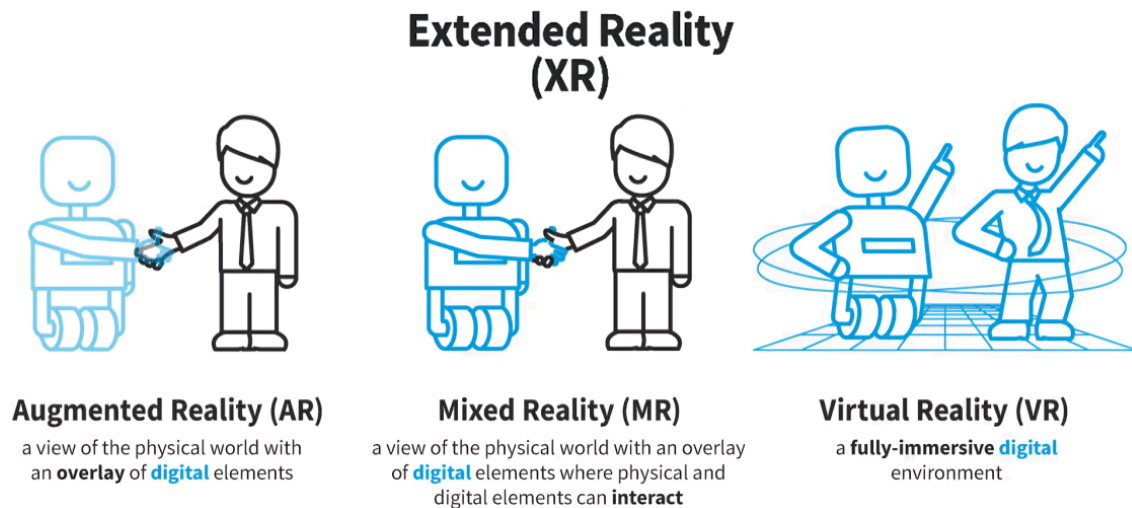


Figure 2.1: XR technologies, including AR, MR, and VR. From [28].

The main feature of XR is its ability to simulate environments, objects, and scenarios in ways that traditional settings cannot. When engaging users through sight, sound, and movement, XR supports more intuitive understanding of complex information and allows for practice in safe, repeatable conditions. In professional and educational settings, this means that XR can be used for things like hands-on training, procedural rehearsal, interactive exploration of data or structures, and even remote collaboration in shared virtual spaces. This technology is most commonly used in education, architecture, design, entertainment, and media [29]. In education and training, it enables learners to explore environments that are otherwise difficult to access, such as inside the human body, the interior of complex machines, remote geographical locations, or abstract scientific phenomena. This makes it especially valuable in areas that rely on spatial understanding, procedural accuracy, and decision-making under pressure.

As technology continues to evolve, XR is becoming more and more accessible and adaptable, with applications ranging from mobile-based AR tools to advanced VR simulations, where its flexibility and growing availability are making it an increasingly relevant tool for both learners and professionals. The following sections will explore each of the core XR components — AR, MR, and VR — in greater detail, highlighting their unique features and potential uses.

2.2.1 Augmented Reality (AR)

AR enhances the real-world environment by overlaying computer-generated elements such as images, data, and interactive graphics onto the physical surroundings [30], thus changing what the users perceives in their environment [31]. Among the three primary forms of XR, AR is the least immersive, as it maintains the user's uninterrupted view of the real world while simply adding layers of digital information, as seen in Figure 2.2.

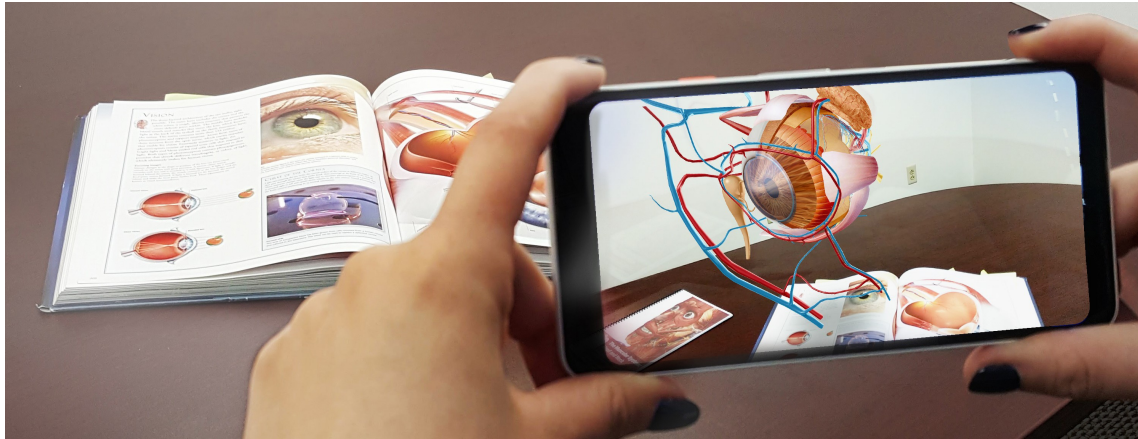


Figure 2.2: AR application for medical education. From [32].

Typically accessed through devices with a camera like smartphones [33], tablets [34], or smart glasses [35], AR analysis a live video feed using computer vision to recognize objects, surfaces, or spatial markers in the environment. Once a target is identified, the system retrieves relevant digital content, from a cloud-based source, and superimposes it onto the user's view, aligned with the physical context. Unlike conventional 2D (Two-Dimensional) interfaces, AR presents information in a 3D (Three-Dimensional) scene that is responsive to the user's movement and orientation. As the user moves and shifts position, the digital overlays dynamically adjust in size, angle and visibility, maintaining proper alignment, thus creating an experience that is both physical and virtual. All this is possible thanks to the use of a digital twin - a virtual model of a physical object or system that resides in the cloud. This model is used as the bridge between the digital content and the real-world objects. Created through computer-aided design or through digital scanning of physical items, the digital twin reflects live data from connected systems, enabling the AR platform to render contextually accurate overlays.

AR's applications cover a broad range of fields, including assistance, navigation and tourism, and many others. As an example, in medicine, AR was found to help in increasing the performance of trainees on ultrasound-guided central venous catheter placement, as well as in decreasing their cognitive load during the procedure [36]. As the technology improves and becomes easily available, AR continues to play an increasingly prominent role in how individuals interact with information embedded in the world around them.

2.2.2 Mixed Reality (MR)

Positioned between AR and VR in terms of user immersion, MR blends real-world elements with virtual ones into a single real-time experience [37]. Thus, MR enables digital objects to be spatially aware, responsive, and integrated into the user's immediate surroundings, as seen in Figure 2.3.



Figure 2.3: MR in the operating room. From [38].

MR systems are usually accessed through head-mounted displays equipped with a range of sensors, including screens, cameras, and motion sensors [39]. These sensors construct a digital representation of the surrounding environment, enabling virtual content to be mapped onto real-world surfaces with high spatial fidelity. As the user moves, the system adjusts the position and behavior of digital elements to maintain their alignment with the physical world, creating the illusion that virtual objects coexist with and respond to real ones. MR experiences support two-ways interactions: the user can engage with digital content through gestures, eye movement, or voice commands, and the virtual content, in turn, can respond to the spatial configuration and user behavior. The result is an interactive interface that extends beyond the screen and into the physical world, where virtual elements appear to occupy space, cast shadows, and persist over time.

This technology has found applications in fields where spatial understanding, interaction, and real-time contextualization are central. In education and training, it can be used to facilitate fast employee training while at the same time reviewing their work for faults [40][41]. Beyond industrial and educational contexts, MR has also been applied in robotics, with Chen *et al.* using it in collaborative human-machine interfaces, such as systems that allow users to monitor and direct autonomous robots within a shared spatial map [42]. By integrating virtual objects so precisely into physical surroundings, MR creates a seamless interface that narrows the gap between real and digital. This convergence paves the way for fully immersive digital environments.

2.2.3 Virtual Reality (VR)

VR is at the opposing from AR when it comes to the reality-virtuality continuum, as it involves a computer-generated simulation that immerses users in an artificial environment, isolating them from the real world [43], as demonstrated in Figure 2.4. Despite this, VR can be categorized as immersive, when it fully surrounds the user for an interactive experience, or non-immersive, when it limits interaction to viewing the environment on a standard screen [44].



Figure 2.4: Application of VR in medical education. From [45].

The illusion of presence is created by VR, consequently giving users the sensation of being physically situated within a virtual place. This is made possible through the alignment of visual, auditory, and, in some cases, haptic stimuli; as users move their bodies, the virtual scene updates accordingly, preserving depth, scale, and perspective to reinforce realism. Unlike AR or MR, where digital elements coexist with the physical world, VR intentionally isolates the user from their surroundings, promoting deeper focus and engagement within the constructed experience. The level of control VR gives over variables such as environment, pace, and complexity makes it an attractive tool across a wide range of sectors. It can be used in areas where realism, repeatability, or experiential learning are critical. In medicine, VR represents 81% of the usage among other XR technologies [46], and can be used in many ways such as testing of prosthetics design's by amputees, without requiring a physical device at early stages [47].

Successful VR experiences depend on both technical precision and thoughtful instructional design. On the technical side, head-mounted displays must deliver high-resolution visuals, wide fields of view and low-latency tracking, while spatial audio and emerging haptic feedback reinforce the illusion of presence and reduce discomfort. From a pedagogical perspective, VR scenarios should match clear learning goals, start with simple tasks that get harder step by step, and include feedback or progress tracking so instructors can see how learners are doing.

2.3 XR in Portuguese Medical Education

In Portugal, the use of XR in medical education is expanding, although more widespread in some institutions and largely focused on simulated-based learning. Rather than being integrated uniformly across curricula, XR tends to appear in targeted training modules or simulation centers.

Several private and academic institutions have adopted XR to mainly enhance clinical training, the majority making use of VR technologies. CUF, a prominent healthcare group, has implemented a variety of simulators across its training programs (Figure 2.5). The Heartworks® system uses AR to train users in transthoracic and transesophageal echocardiography using a 3D virtual heart. Bodyworks Eve®, an ultra-realistic female patient simulator, allows for bedside ultrasound training in emergency settings. CUF also utilizes GI-BRONCH Mentor™ and Mentice®, both high-fidelity virtual reality simulators. The former supports endoscopic procedure training recognized by leading medical societies, while the latter mimics a fully functional catheterization lab with physiological modeling, haptic feedback, and realistic imaging, offering an immersive and pressure-responsive learning environment.

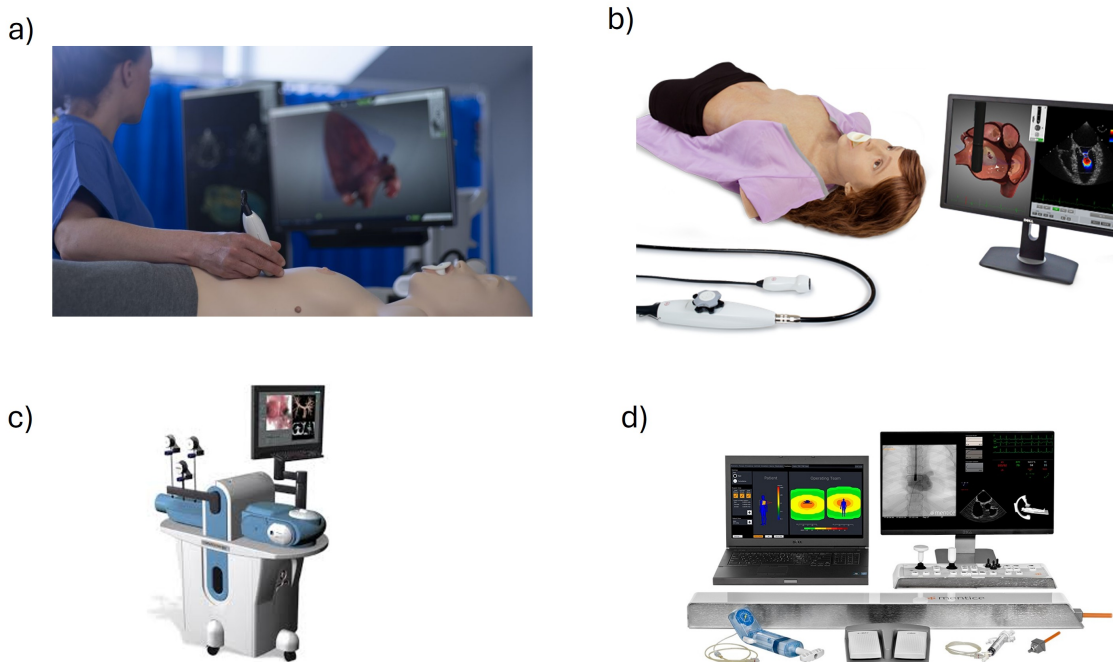


Figure 2.5: XR technologies at CUF's simulation center. a) Heartworks®; b) Bodyworks Eve®; c) GI-BRONCH Mentor™; d) Mentice®.

In a similar way, the FMUL has available EndoVR™ and LapVR™, which provide virtual environments for endoscopic and laparoscopic skills practice, with visual and tactile feedback, and the VIST® G5, a portable high-fidelity endovascular simulator for hands-on procedural training. All three of these technologies can be seen in Figure 2.6.

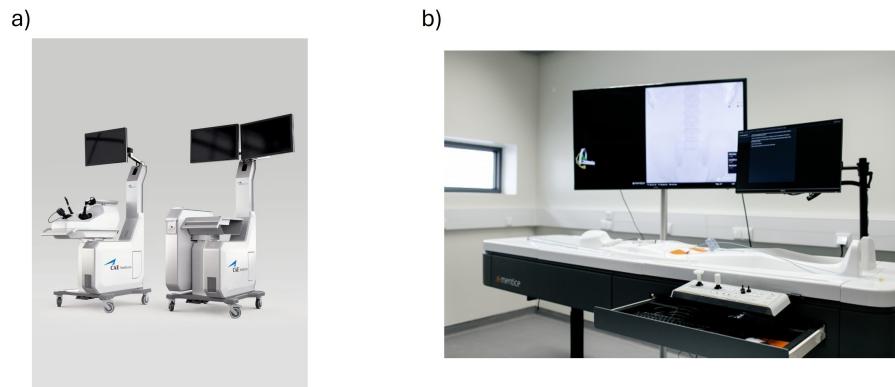


Figure 2.6: XR technologies at the simulation center of the FMUL. a) EndoVR™ and LapVR™; b) VIST® G5.

Hospital da Luz has also invested in several XR tools (Figure 2.7), focusing on ultrasound and catheterization procedures. These include simulators for transthoracic, transesophageal, and trans-abdominal ultrasound using Bodyworks Eve®, as well as the ScanTrainer system for transvaginal and transabdominal imaging. For cardiovascular interventions, the institution employs the ANGIO Mentor simulator, designed for training in catheterization techniques.



Figure 2.7: XR technologies at Hospital da Luz. a) Bodyworks Eve®; b) ScanTrainer; c) ANGIO Mentor.

Chapter 3

State of the Art

This section explores the current research landscape on the use of XR in medical education. Branched into four distinct sections, this analysis aims to assess the current state of XR for medical education while identifying the main challenges for its inclusion into medical curriculum.

3.1 Research Process

To analyze the current landscape of XR in medical education, a systematic literature review was conducted across two key academic databases: PubMed and Scopus.

The initial search strategy utilized the following broad query ("**extended reality**" OR "**mixed reality**" OR "**augmented reality**" OR "**virtual reality**") AND "**medical education**". This approach aimed to capture a wide range of studies related to the application of immersive technologies in healthcare education. However, it yielded more than 2,000 articles, indicating that the query was too broad for a focused review. Thus, to refine the results and ensure relevance within the limited timeframe available to complete the state of the art, the search strategy was adjusted. The refined query became: ("**Extended Reality**" OR "**Mixed Reality**" OR "**Augmented Reality**" OR "**Virtual Reality**") AND "**medical education**" AND "**medical students**" AND ("**survey**" OR "**questionnaire**"). This modification targeted studies that specifically assessed the effectiveness of XR technologies among medical students. By incorporating the keywords "medical students," the search focused on empirical studies pertinent to this demographic, while the inclusion of "survey" or "questionnaire" ensured that only research using systematic data collection methods was considered.

A total of 88 articles were collected, 20 from PubMed and 68 from Scopus. The selection process followed certain criteria: only articles in English and Portuguese were included, the publication window was set from 2023 to 2024, and only open access materials were considered. The review process was improved using the Rayyan platform [48], which simplifies the organization of the articles and improves efficiency. With its user-friendly interface, Rayyan allows

semi-automated selection of abstracts and titles, expediting the initial review steps [49]. In addition, the platform was instrumental in carrying out a duplicate check, identifying a total of 15 duplicate articles. Moving on to the screening process, and by adhering to the inclusion criteria — specifically addressing XR technologies within the context of medical education and focusing on medical students — 21 articles were excluded for the following reasons: 8 were not within the context of medical students, 8 were unrelated to XR, 3 did not pertain to medical education, 1 neither mentioned XR nor addressed medical education, and 1 did not focus on educational outcomes.

Ultimately, 52 studies were included in this section, where Figure 3.1 showcases the search strategy and list of excluded articles. Additionally, a summary table can be consulted in Appendix A with the selected articles, recording details such as article identification, year of publication, journal, technology, application, educational indicators, advantages, disadvantages, and future work.

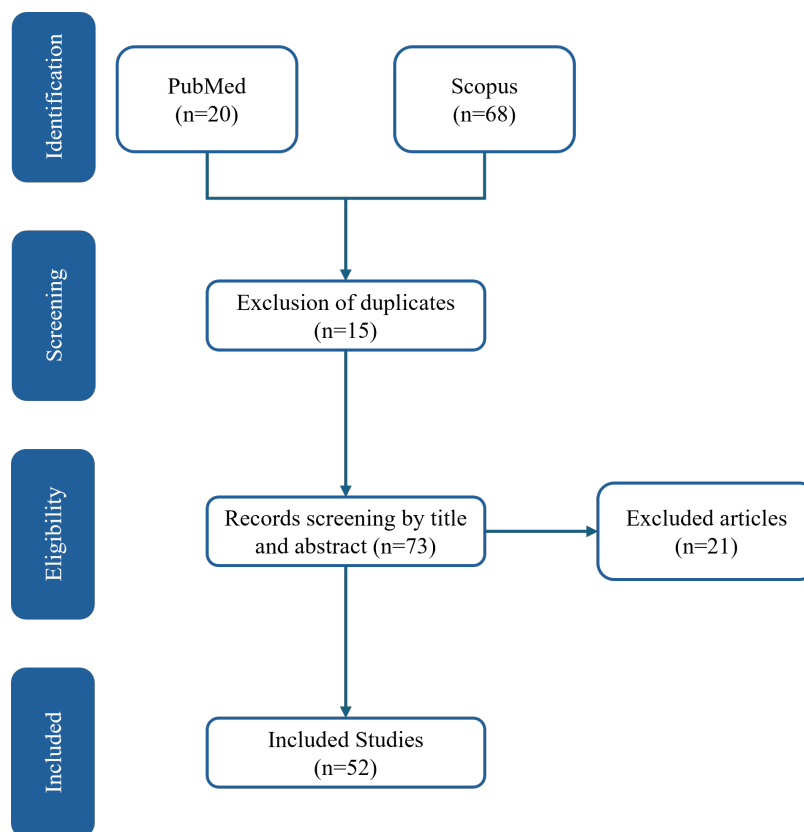


Figure 3.1: Flow diagram illustrating literature research, exclusion process, and number of included studies in the literature review.

3.2 XR in Theoretical Medical Curriculum

XR holds significant promise in theoretical medical education. Given the extensive knowledge medical students are required to master across challenging courses, XR can enhance the learning experience by making complex concepts more engaging and comprehensible. By creating dynamic and interactive environments, XR facilitates the absorption of complex material, making it more accessible and engaging for students.

The study by Pieterse *et al.* evaluated the use of 360-degree video-based VR applications for small group learning sessions aimed at improving students' preparedness for clinical clerkships. It was found that 59% of students rated VR as a good learning tool, while 26% rated it as excellent. Most students enjoyed the VR experience (average score 4.5 out of 5), and 45% felt it was important for the university to further pursue VR in education [50].

In embryology education, Ryan *et al.* investigated the use of a Virtual Reality Learning Environment (VRLE) to teach fetal development. It was found that both the VRLE and PowerPoint tutorial groups showed increased knowledge after the learning experiences, but only the VRLE group retained knowledge at the 1-week follow-up. The VRLE group also reported higher satisfaction and self-confidence in learning, concluding that VRLEs can enhance understanding and retention of complex, less accessible concepts in medical education [51].

In their study, d'Aiello *et al.* explored the use of MR with Microsoft HoloLens for teaching third-year medical students about sinus venosus atrial septal defect with partial anomalous pulmonary venous return. The results showed that students using MR performed better in proficiency tests, particularly in understanding anatomy and treatment planning, compared to those using traditional slides. Additionally, the MR group reported high satisfaction, with a net promoter score of 72 [52].

Gao *et al.* evaluated the use of 3D virtual reality simulations to teach human parasitology, specifically schistosomiasis prevention and control. The study found that students in the simulation group had significantly better knowledge acquisition and retention, as well as more positive changes in their subjective task values, particularly regarding the importance of the topic, compared to the lecture group [53].

Regarding pathology education, Moro *et al.* used AR models as a supplement to traditional learning with physical specimens. It was noted that 71.6% of students found AR beneficial for viewing multiple angles and orientations, and 89.2% preferred a combination of AR and physical specimens for optimal learning [54].

In otolaryngology, Malike *et al.* evaluated the use of HoloLens2™ in remote teaching for medical students. Students in the HoloLens2™ group showed significantly greater improvement in quiz scores (60% increase compared to 45% in the control group) and were more likely to ask questions during the sessions. Additionally, the majority of students felt the technology enhanced engagement and helped visualize complex concepts more easily [55].

Michalski *et al.* studied the use of MR technology for asynchronous learning of heart anatomy. The results showed that MR activities were less cognitively demanding in terms of task difficulty

and complexity compared to synchronous classroom and laboratory activities. Participants reported that the MR activity was more relevant to their studies and allowed them to focus more on the learning task. Additionally, the MR technology allowed students to interact with 3D anatomical models, which reinforced their learning without overburdening their cognitive resources [56].

Hutchcraft *et al.* explored the use of smartphone/tablet applications and immersive VR, in teaching obstetric anatomy and physiology to second-year medical students. The majority of students (63.2%) frequently used smartphones for the smartphone/tablet platform, finding it convenient and portable, while immersive VR use was minimal. Those who used immersive VR enjoyed the interactive features, but some felt the software's visual content lacked sufficient detail [57].

In anatomy education, da Cruz Torquato *et al.* examined the use of VR in conjunction with traditional learning methods for medical students. The study found no significant improvement in academic performance between VR and traditional methods, but students reported a high level of satisfaction with VR, particularly for its ability to enhance 3D visualization of anatomical structures [58].

Regarding online learning of clinical medicine, Stackhouse *et al.* found that knowledge attainment was comparable across MR, video-based, and case vignette tutorials. Students reported higher engagement and enjoyment with the case vignette method, though MR was considered effective, acceptable, and feasible for large-scale clinical teaching [59].

In pharmacology education, Kim *et al.* evaluated the use of VR for teaching cardiovascular drugs and autonomic nervous system drug actions. The results indicated that participants showed a significant improvement in knowledge and self-rated confidence in pharmacology after using the VR module. Additionally, 90% of participants expressed satisfaction with the module, found it easy to use, and believed their time was efficiently used [60].

In anatomy education, Lia *et al.* evaluated the use of VR-based anatomy instruction videos for large classes with limited equipment. They found that 54.85% of students agreed the videos were beneficial for learning gross anatomy, though only 18.56% felt VR could replace cadaver dissection [61].

The study by He *et al.* investigated the integration of VR with Case-Based Learning (CBL) in medical education. It found that students using VR plus CBL outperformed those with traditional CBL, especially in anatomy tests, and reported higher satisfaction with teaching methods and skill improvement [62].

Rudolphi-Solero *et al.* evaluated the use of a competitive game in the metaverse (Second Life) for interuniversity radiology learning. Participants found the experience valuable for reinforcing their knowledge, with 85.6% providing positive feedback. The competition promoted team collaboration, and 34.5% of students appreciated the virtual relationships and social interaction during the Covid-19 pandemic [63].

Augmented 360-degree 3D VR videos were used to enhance neurosurgery education for medical students by Truckenmueller *et al.*. The immersive experience, featuring superimposed elements like neuroimaging and illustrations, improved students' understanding of surgical procedures and operating room workflows. The videos increased interest in neurosurgery and helped

prepare students for clinical rotations by providing orientation and boosting confidence [64].

The AEducAR 2.0 study, conducted by Neri *et al.*, evaluated the use of AR combined with 3D-printed anatomical models. It was noted that 79% of participants enjoyed the experience, with 92% expressing interest in similar AR-based activities for other anatomy modules. Additionally, 94% of students found AR helpful for studying, and 95% believed it would be beneficial in their future medical careers, with 90% indicating that AR could improve their practical skills [65].

Wach *et al.* surveyed 150 German medical students regarding the integration of MR into neurosurgical education. The study found that 87.3% of participants were interested in a neurosurgical MR class, and 94.7% believed that MR would enhance their understanding of neuroanatomy and surgical approaches. Furthermore, 72.7% of the students agreed that such a course would increase the likelihood of using MR technology in their future medical careers. The majority of students also preferred that MR classes be introduced early in their medical education, ideally during the second year [66].

In a study by Abundez Toledo *et al.* regarding the use of VR in anatomy education, it was found that 90% of medical students believed VR would enhance their learning of anatomy compared to traditional lectures. Additionally, 94% agreed VR should be available to medical students, and 75% saw its potential for other subjects. Most participants also expressed interest in using VR for their training if available [67].

Würstle *et al.* explored the application of VR simulations in teaching pancreatic cancer-related topics such as anatomy, diagnosis, and treatment. The findings demonstrated a significant improvement in knowledge, with average test scores rising from 4.0 to 7.3 out of 10. Furthermore, 84.6% of students expressed heightened interest in the subject matter, and 70.9% reported feeling motivated to delve deeper into the course material [68].

3.3 XR for Skill Development in Medical Training

XR serves as a powerful tool for simulation and skill development in medical training. It provides a safe and controlled environment where medical students can practice procedures and refine their skills without the risks associated with real-life scenarios.

In ophthalmology, Deuchler *et al.* examined the use of the Eyesi slit lamp simulator to improve slit lamp examination skills. It was found that students in the simulator group performed significantly better in the objective structured clinical examination, with higher scores in areas such as adjusting slit lamp settings, recognizing anatomical structures, and applying illumination techniques. Students reported increased confidence and knowledge in diagnosing pathologies and applying slit lamp skills [69].

A survey, by Mergen *et al.* conducted with 252 medical students at Saarland University found that 95.2% of participants supported the integration of VR into medical education. The students were particularly interested in using VR for practical courses, with a preference for specialties like surgery and emergency medicine, as VR can help train clinical decision-making and procedural

skills in a risk-free environment. Participants also emphasized the potential of VR in preclinical education, especially for anatomy, and acknowledged its ability to simulate rare diseases and clinical reasoning [70].

VR was assessed as a tool for emergency medicine training by Mahling *et al.*, where 91% of students agreed that VR is useful for conveying complex issues quickly, and 88% considered it a valuable addition to traditional mannequin-based training. Furthermore, 80% of students supported the use of VR simulations for examinations, highlighting strong enthusiasm for VR as a supplemental learning tool in emergency medicine [71].

An evaluation on the use of 360-degree VR scenarios integrated with multiple-choice questions, to assess medical students' skills, was conducted by Knudsen *et al.* The VR simulations provided a high level of presence and immersion, with participants across all experience levels rating the simulations positively. The scenarios were mentally engaging, and participants in more experienced groups rated their performance higher [72].

A VR simulation was used to train practical skills in musculoskeletal wrist X-ray. Jensen *et al.* found that 90% of participants strongly agreed that the X-ray room in the VR simulator was realistic, and that the VR simulator could contribute to learning in radiography education [73].

In neurosurgery, the study by Silvero Isidre *et al.* investigated the use of MR in an undergraduate neurosurgical hands-on course. It was found that students in the MR group reported significantly higher satisfaction scores compared to the conventional group. Additionally, a majority of MR group participants considered the technology engaging and beneficial, and expressed support for the increased use of MR in medical curricula [74].

Participants of the study by Jacobs *et al.*, which utilize VR for sepsis identification and management simulation by healthcare professionals, reported high immersion and intrinsic motivation. Cognitive load was moderate, suggesting a balanced challenge. Usability was positive, indicating effective technology use. The debrief session showed strong emotional engagement and reflection, highlighting the simulation's effectiveness in enhancing learning and reflective practice [75].

Cheung *et al.* explored the use of a VR training model to teach medical students vaginal examination skills. It was noted that 84.7% of the participants found the instructions clear, and 92.4% reported that the training helped them recall the details of the tasks. Additionally, 66.2% of students felt motivated to learn through the VR training model, highlighting its potential to enhance both learning and interaction [76].

VR simulation was used to teach tendon suturing and its effects on clinical practice by Gan *et al.* It was found that students in the VR group showed better clinical practice scores, particularly in urology and orthopedics, and exhibited a stronger commitment to reviewing relevant theoretical knowledge during their internship. The study also noted that VR simulation enhanced the students' motivation for active learning and contributed to a better learning experience [77].

The HoloLens, an AR head-mounted display, was evaluated for its effectiveness in enhancing anatomy learning and medical training. Gsaxner *et al.* found that several studies indicated improved student engagement and motivation, although the benefits over traditional methods like cadaveric learning or other computerized methods were minimal. The HoloLens was particularly

useful in providing visual feedback for training tasks and in enhancing medical simulators, although more innovative, dynamic content and interactive models have yet to be explored in depth [78].

In emergency medicine, Rickenbacher-Frey *et al.* developed and evaluated a VR simulation for managing patients with acute dyspnoea. The study found that after the VR training, participants' confidence in treating dyspnoeic patients significantly increased. Additionally, the VR training was praised for its high usability, user satisfaction, and minimal simulator sickness, with participants appreciating the peer teaching approach during sessions [79].

In neurosurgery, Guerrini *et al.* evaluated the use of hands-on simulation practices, including AR, such as suturing and microvascular anastomosis. It was noted that 77.5% of the participants were increasingly interested in following a surgical path and that 72.7% stated an enhanced confidence in maneuvering surgical instruments [80].

Deuchler *et al.* made use of the Slit Lamp Simulator, integrating VR technology, to assess its benefits. It was revealed that the medical students' overall performance in a fundus biomicroscopy objective structured clinical examination was higher in the simulator group, rather than the traditionally trained group. Therefore, students learned fundus biomicroscopy and identified pathologies more effectively with the simulator [81].

In knee aspiration, Singh *et al.* investigated VR as a teaching method for fourth-year medical students. Students were divided into three groups: Group A received a lecture, Group B had hands-on practice, and Group C experienced VR training. Group C scored significantly higher on the objective structured clinical examination and reported increased confidence and understanding of the procedure [82].

In a study by Mergen *et al.*, medical students in their fifth or sixth clinical semester utilized the Valve Index VR-Kits to conduct complete skin cancer screenings. This study demonstrated a strong positive attitude among students towards VR integration, with a significant increase in their perceived self-competence [83].

Alieldin *et al.* explored the use of VR to teach empathy to medical students by immersing them in scenarios highlighting the loneliness and social isolation experienced by older adults. After participating in the VR training, students showed significant improvements in their empathy scores and reported applying what they learned during clinical interactions [84].

Johnston *et al.* explored the use of MR through the Microsoft HoloLens 2 to teach airway management to medical students in a clinical setting. The study involved 47 students who participated in MR-based tutorials, which included both real patient interactions and 3D anatomy teaching. The results showed that the MR tutorial was seen as more beneficial than PowerPoint presentations and comparable to live patient encounters. Students expressed positive feedback, indicating that MR teaching supported learning, and they were open to incorporating more MR-based education in the future [85].

In dermatology, Junga *et al.* evaluated a VR simulation for skin cancer screening in medical education, and it was found that 74.7% of students correctly identified at least one melanoma. Students rated the simulation positively, with 4.36/5 for enjoyment and 4.08/5 for skill practice. The

VR scenario led to a significant increase in students' competence, with the greatest improvement occurring during the simulation [86].

In abscess incision training, Nuutinen *et al.* evaluated the use of fully immersive VR simulation compared to video lecture. It was noted that both methods increased students' knowledge and self-confidence equally, with participants in the VR group showing greater learning gains when technical support was available. Additionally, 83%-100% of participants found the VR and video training physically, mentally, and educationally suitable, though video was rated higher for technical usability [87].

Liang *et al.* assessed the use of virtual simulation experiments for basic medical training. The authors found that learning motivation and task value were significantly correlated with learning satisfaction, while self-efficacy had no significant effect. The study emphasized the importance of course content, technical support, and embodied presence in enhancing satisfaction, with factors such as interface design and technical reliability playing key roles in improving student learning outcomes [88].

In training for emergency scenarios, Walls *et al.* evaluated the use of 360-degree VR simulation for scenarios such as cardiac arrest and life-threatening asthma. It was noted that students using VR had significantly higher engagement levels (6.4% more time on task) and enjoyment levels compared to standard desktop simulation. Additionally, physiological measures such as heart rate were also higher during VR simulations, indicating greater cognitive engagement [89].

Malone *et al.* assessed the use of VR and high-fidelity simulations to assess skills in recognizing a patient needing urgent or emergent care and initiating proper evaluation and management in medical students. It was found that VR simulations, while useful for formative assessments, led to significantly lower entrustment ratings compared to high-fidelity simulations, with only 65.5% of students demonstrating competence in VR, compared to 91.7% in high-fidelity. Students reported enjoying the VR experience, with 13% describing it as "fun" and "interesting" [90].

In intensive care medicine, a pilot study by Willis *et al.* used assisted reality glasses to live stream intensive care unit teaching sessions to medical students. Students reported high satisfaction, with 85% finding the sessions relevant to their learning needs and the technology enhancing their understanding of intensive care unit equipment and procedures [91].

Jensen *et al.* evaluated the use of VR simulation to train participants in assessing and repositioning lateral wrist radiographs. It was noted that 72% of participants accurately assessed radiographic positioning, while 51% successfully repositioned the wrist in the correct direction for a retake. The study highlighted the feasibility of using VR for skill refinement without involving patients or radiation exposure [92].

A study on the use of MR headsets to simulate high-acuity trauma scenarios for junior medical trainees found that MR training resulted in significantly higher clinical knowledge scores both during and two weeks after the course compared to traditional teaching methods. All participants who underwent MR training received satisfactory appraisals from their supervisors, indicating improved preparedness for trauma management. Feedback from trainees also revealed an increased

sense of confidence and readiness to handle real-life trauma situations, as reported by Clarke *et al.* [93].

Pedram *et al.* assessed the use of head-mounted display VR for skill development, specifically in arterial blood gas collection. It was found that students who underwent VR training significantly outperformed the control group in practical clinical tasks, with a 32.4% improvement in performance and a 39.7% improvement in adherence to safety and hygiene procedures. The study group also reported increased self-efficacy and a higher completion rate of the procedure compared to the control group, with a 40% lower error rate [94].

Einloft *et al.* tested XR/VR-based simulation training for medical emergencies. They found that 84% of students found the head-mounted display and simulation intuitive, and 91% viewed VR as an effective learning tool. 76 % believed VR would improve real-life responses, and 71% saw it benefiting their future careers [95].

In trauma care, when using VR trauma simulations as an adjunct to the advanced trauma life support course, Birrenbach *et al.* found that, although there were no significant improvements in objective performance measures, participants in the VR intervention group reported significantly increased confidence in treating polytrauma patients post-training. Additionally, the VR simulation was well accepted by the participants, with high scores for usability, immersion, and satisfaction [96].

In obstetrics and gynecology, Dunlop *et al.* evaluated the use of a VR learning environment for teaching postpartum hemorrhage management and balloon insertion. Both VR and traditional teaching improved students' knowledge and confidence. VR participants completed the balloon insertion faster and 100% enjoyed the experience, with 82.4% likely to recommend VR in medical education [97].

Schöbel *et al.* implemented an immersive VR operating theater on orthopedic surgery as an elective course for medical students. It was noted that 91% of participants expressed interest in further VR training, with all students stating that immersive VR improved their understanding of surgical procedures and 67% believing it enhanced their surgical skills [98].

In clinical microbiology, Meng *et al.* combined teaching method of virtual simulation and real experiments. 85% of students were satisfied with the virtual simulation, and 89% felt it helped them better understand microbiological testing and improve clinical thinking. Students using the combined approach performed better in both practical and theoretical tests than those who received only traditional teaching methods [99].

Stauffer *et al.* utilized an AR training application for teaching needle placement with the cube navigation system. The AR group showed reduced cube rotation and fewer placement errors compared to the conventional training group. Participants also rated the AR training more positively for engagement, intuitiveness, and reliability [100].

In the study by Lovett *et al.*, the use of AR for suturing skill development was evaluated among medical students using the Microsoft HoloLens. The results showed that students who used the AR guidance system demonstrated significant improvements in the number of stitches placed, stitch

spacing, and symmetry compared to those who practiced independently. Participants also reported that the AR application was useful for guiding suture placement and spacing [101].

3.4 Challenges of Integrating XR in Medical Education

The implementation of XR in medical education may presents a range of challenges, factors such as cost, training requirements, and content quality can complicate the integration of these technologies. These and other challenges must be carefully considered to effectively incorporate XR into medical curricula.

Physical discomfort, such as cybersickness and motion sickness, is a common issue. Many students report symptoms like dizziness, nausea, and disorientation during VR or MR sessions, particularly after prolonged use, which affects learning experiences and can discourage future use of the technology [50][51][61][68][83][96]–[98]. Technical problems, including device malfunctions, calibration errors, and poor connectivity, also hinder effective learning. These disruptions can prevent smooth interaction with the simulations, making the experience less immersive and less effective [55][63][85][98]. Additionally, the lack of tactile feedback, which is crucial for medical practice, limits the realism of many XR simulations, affecting skills development in fields like surgery and anatomy [54][73][74][86].

The financial costs of XR technologies are also a significant barrier. The high expenses associated with purchasing and maintaining the necessary equipment, software, and infrastructure make it difficult to integrate XR into curricula, especially in institutions with limited budgets. This issue is compounded by the labor-intensive process of developing tailored XR content for specific educational purposes [60][64][82][89][90]. Furthermore, there are concerns about the applicability of skills learned in virtual environments to real-world clinical settings, as some XR simulations struggle to accurately replicate the complexity of hands-on medical practice [88][89][92]. The cognitive load required for students to process complex information in immersive environments is another challenge. VR and MR scenarios often involve multitasking and information overload, which can detract from the learning experience [79][88][93].

Social and logistical barriers also play a role in limiting the effectiveness of XR in medical education. Many students are initially reluctant to engage with XR technology, particularly if they are unfamiliar with immersive systems. In some cases, students prefer traditional learning methods over XR-based approaches, highlighting the need for a balanced integration of both [57][94]. Additionally, the time required for proper preparation, as well as the logistical challenges of coordinating XR-based learning for large student cohorts, can strain resources and hinder widespread adoption [59][91]. Another issue is the lack of real-time interaction and feedback from instructors in XR environments, with some students preferring a more hands-on, human-centered approach to learning [75][90][94]. Finally, concerns over the long-term sustainability of XR programs arise, especially regarding continued access to resources and the potential diminishing benefits without ongoing support and updates [63][77][95].

Chapter 4

Methodology

This chapter describes the methodology used to assess medical students' perceptions regarding the integration of XR technologies in medical education. The aim is to evaluate how students' experience, knowledge, and attitudes toward XR — including AR, MR, and VR — relate to their perceptions of its educational potential. It begins with Section 4.1, explaining the survey method used to gather data. Section 4.2 describes the sample and sampling approach. Section 4.3 explains how the survey was tailored and tested. Section 4.4 address participant confidentiality and consent. Section 4.5 outlines survey distribution and response rates, while Section 4.6 covers the statistical methods applied. Finally, Section 4.7 discusses factors affecting the study's generalizability.

4.1 Research Design

The study made use of a survey to explore undergraduate medical students' perspectives on the integration of XR in medical education, where the data collected through it has a categorical nature.

Categorical data refer to information that can be organized into distinct groups based on specific characteristics or attributes, and that can take the form of nominal variables, where the categories have no inherent order, or ordinal variables, where the categories follow a ranked sequence. Both these types are present in the gathered data, since the survey included single-choice and multiple-choice questions, as well as Likert scale and rating scale items, which provided data related to students' familiarity with XR technologies, their perceived usefulness, accessibility, and willingness to integrate XR into their education. Additionally, one open-ended question was incorporated to allow participants to share ideas and suggestions regarding the way of use of XR in medical education.

This approach made possible for the study to capture a broad overview of the trends and distributions across key variables, providing the researched insights into students' opinions on XR technologies within their learning environment.

4.2 Study Setting and Participants

The target participants for this study were medical students enrolled at the ICBAS, part of the Universidade do Porto (U.Porto). Eligibility criteria required participants to be actively studying from the first to the sixth year of the medical program.

A non-probabilistic voluntary sampling method was used. Students were invited to participate through an internal communication strategy, so as to try and boost response rates: targeted faculty members at ICBAS were contacted, who subsequently forwarded an invitation email to their students.

In total, approximately 20.75% of all medical students, enrolled in the academic year of 24/25, completed the survey. Although the sample was not selected through random methods and does not aim to be statistically representative of the entire medical student population, it nonetheless includes a diverse group of students across different academic years.

4.3 Survey Adaptation and Pilot Testing

The research instrument utilized in this study (Appendix B) had its origin in one of the studies [70] included in the literature review from Chapter 3. Permission to use and adapt the survey was requested via email and obtained from the study's main author.

Following this, the original survey was meticulously reviewed to ensure its relevance to both the dissertation's theme and the context of Portuguese medical education. This resulted in a few questions being added, divided into two, or slightly rephrased to better reflect the Portuguese medical system, ensuring that participants would fully understand the questions posed. Additionally, the survey was translated from its original language into Portuguese to ensure accessibility, keeping in mind the maintenance of the integrity and meaning of the questions. The final version of the survey was then reviewed multiple times by the research team to ensure clarity and coherence.

Prior to the official distribution of the survey, a pilot test was conducted with 29 undergraduate medical students from various institutions outside of ICBAS, among them FMUL, and Escola de Medicina da Universidade do Minho. The feedback from these participants revealed no issues with the clarity, structure, or design of the survey, which affirmed that it was easy to understand and would possibly yield reliable data. The final version was then submitted for the necessary ethical approvals.

4.4 Ethical Considerations

Ethical approvals, a crucial part of this study, were obtained from two institutional bodies: the Unidade de Proteção de Dados da U.Porto and the Comissão de Ética do Centro Hospitalar

Universitário de Santo António (CHUdSA)/ICBAS. The approval process required, among others, completing the necessary documentation for each institution, submitting the full survey for review, and creating a brochure with the study's information to be made available to participants (Appendix C).

Participation in the study was entirely voluntary, and students were assured of their anonymity and confidentiality, as no personally identifiable information was collected during the survey process. At the same time, participants were informed that they could withdraw at any point before submitting their answers, without any negative consequences, and that their answers would be deleted once the study were completed. Prior to beginning the survey, participants were presented with written information about the study's purpose, procedures, and data handling practices, ensuring informed consent. This consent was considered given when participants, after reading the introductory explanation, chose to proceed with answering the survey and submitting said answers.

With ethical guidelines in place, the study moved on to the data collection phase, where the survey was used to gather responses from participants. The following section outlines the process by which data was collected.

4.5 Data Collection

The data collection took place between early February, aligning with the start of the second semester at ICBAS, and the end of April. The survey was distributed electronically, with participants receiving an invitation via email, which included a brief explanation of the study's purpose, along with a Quick Response (QR) code, and a direct link to access the survey. To help boost participants, several reminders were sent out throughout the data collection period. These reminders were received by targeted faculty members to request them to remind their students about the survey's availability.

The survey was completed by students at their convenience, and the mean completion time was 8 minutes and 7 seconds. This was facilitated by the online format of the survey, hosted on Microsoft Forms, thus originating an anonymous database containing the students' answers. The data were exported to an Excel spreadsheet and stored in OneDrive, a cloud storage device, linked to a licensed student account at the Faculdade de Engenharia da Universidade do Porto. This platform provided secure data storage, making sure that all information was protected from unauthorized access and properly backed up to prevent data loss.

This approach to data collection aimed to ensure that the information gathered was both reliable and ethically managed. With the responses securely stored, the study could proceed to the data analysis phase.

4.6 Data Analysis

The analysis of the collected data was carried out using IBM SPSS Statistics (version 30), a software suited for data management and statistical analysis. Descriptive statistical analysis were applied as an initial step to summarize the distribution of responses across categorical variables included in the study. Frequencies and percentages were also calculated to provide a clear depiction of participants' answers to close-ended items, thus offering an overview of how the medical students' views and experiences with XR were distributed within the sample.

Given that the dataset consisted exclusively of nominal and ordinal variables obtained from the closed-ended survey items, the chi-square test ($p < 0.05$) was selected as the most appropriate statistical method because it is specifically designed to evaluate associations between categorical variables, without requiring assumptions about the underlying distribution of the data. However, if requirements weren't met Fisher's exact test was conducted instead, and if dealing with large datasets Monte Carlo's significance test was used. The chi-square test operates by comparing the observed frequencies of responses across different categories, which are organized into contingency tables that display how the participants' answers are distributed jointly between pairs of variables. By examining the discrepancies between the observed and expected frequencies in these tables, this non-parametric test offers means to judge whether statistically significant associations exists between pairs of variables, helping to identify possible differences in response patterns among subgroups of participants. For the open-ended question, which invited participants to contribute with additional ideas, a word cloud was generated as a means of visually representing the most frequently mentioned terms. This provided a summary of recurring concepts raised by medical students, helping to highlight the dominant themes reflected in their responses.

Together, these analytical methods led to the examination of the dataset from multiple angles, enabling both an inclusive summary of responses and the identification of relevant patterns and associations to inform the interpretation of the study's findings.

4.7 Limitations

While this study provides valuable insights into medical students' perceptions of XR in education, several limitations must be considered when interpreting the results.

One key limitation is the non-probabilistic voluntary sampling method used to recruit participants. Because the survey was voluntary and participants were self-selected, the sample may not be fully representative of the broader medical student population. Students who opted into the survey may have had a particular interest in or experience with XR, which could introduce a selection bias. As a result, the findings may not generalize to all medical students, particularly those who have limited exposure to or knowledge of XR technologies.

The study also focused on a single institution, specifically medical students enrolled at the ICBAS. While this allowed for a manageable and specific cohort, it also limits the external validity

of the results. The perceptions and experiences of ICBAS students may differ from those of students in other universities, either in Portugal or internationally. As such, the findings should be interpreted with caution when considering their application to other educational contexts or medical schools.

Additionally, the study relied on self-reported data, which carries the inherent risk of social desirability bias. Participants may have answered questions in a manner that they believed was socially acceptable or aligned with perceived expectations, rather than reflecting their true beliefs or behaviors. This bias is particularly relevant in topics such as XR, where students might feel compelled to give positive responses about new and innovative technologies in education, even if their actual experiences or opinions are more nuanced.

Finally, the study was conducted over a relatively short period, and while efforts were made to maximize response rates through repeated reminders, it is possible that certain student groups (e.g., those with limited interest in XR or those in their final years) were underrepresented. This could result in skewed perceptions of the overall usefulness and applicability of XR in medical education.

Chapter 5

Results

This chapter discloses the findings obtained from the survey, aiming to highlight patterns, preferences, and associations related to student's perceptions on the use of XR in medical education.

5.1 Sample and Demographics

A total of 226 responses were collected and retained for analysis, representing the approximately 20.75% of medical students mentioned in Section 4.2. All participants were undergraduate medical students at the ICBAS. Given this, the demographic characteristics of the respondents, including gender, academic year, and age group, are showcased in Figure 5.1.

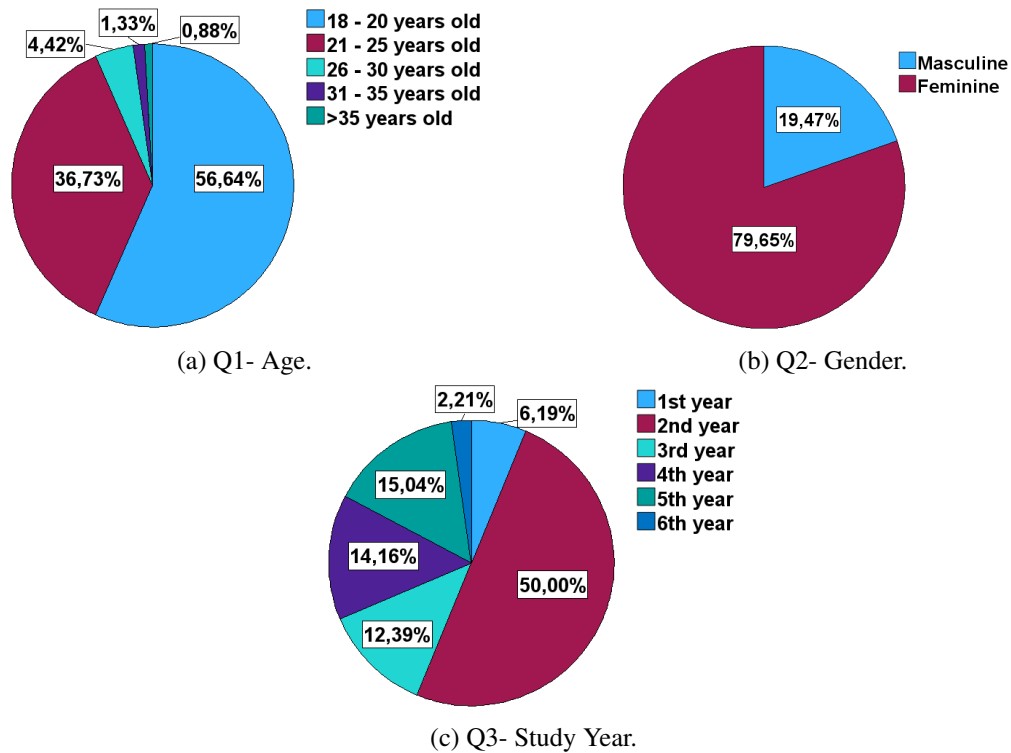


Figure 5.1: Demographic characteristics of the study's population.

In terms of age (Figure 5.1a), respondents represented a range of age groups, spanning from less than 20 years old to over 30 years of age. The majority of participants were young adults, 128 fitting in the category of 18 to 20 years old (56.64%) and 83 in the category of 21 to 25 years old (36.73%). The smallest representation came from 15 participants that were aged 26 years or older (6.63%).

When it comes to gender (Figure 5.1b), participants were predominantly on the feminine side of the spectrum, with 180 students identifying as female (79.65%) and 44 students identifying as male (19.47%). Additionally, students were distributed across all six academic years of the medical curriculum (Figure 5.1c). The largest proportion of students were enrolled in the 2nd year (n=113, 50.00%), followed by the 5th year (n=34, 15.04%). The 6th year represented the smallest subgroup with 5 respondents (2.21%).

A summary of all demographic variables is presented in Table 5.1. The demographic profile shows representation across gender, academic year, and age groups among the respondents.

Table 5.1: Demographic's summary table.

Variable	Category	n	%
Age	18 - 20 years old	128	56.64
	21 - 25 years old	83	36.73
	26 - 30 years old	10	4.42
	31 - 35 years old	3	1.33
	>35 years old	2	0.88
Gender	Feminine	180	79.65
	Masculine	44	19.47
Study Year	1 st year	14	6.19
	2 nd year	113	50.00
	3 rd year	28	12.39
	4 th year	32	14.16
	5 th year	34	15.04
	6 th year	5	2.21

5.2 XR Awareness and Prior Experience

Participant's familiarity with XR and their prior experiences using such technologies were assessed in the survey. Targeted questions captured both conceptual awareness and actual use of XR technologies in different contexts.

The majority of students reported not being aware of the umbrella term "Extended Reality (XR)" (n=172, 76.11%), with only 54 respondents (23.89%) indicating they were familiar with the concept of XR, as depicted in Figure 5.2.

Q4- Reported Familiarity with "Extended Reality (XR)"

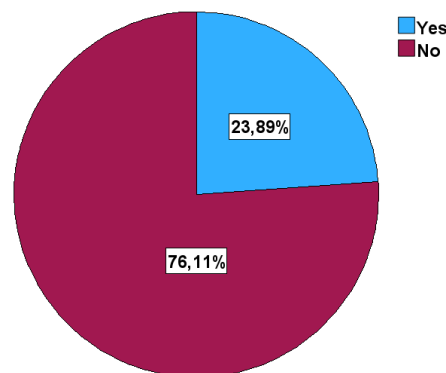


Figure 5.2: Students' rate of familiarity with XR.

No statistically significant associations between participants' age or year of study and their self-reported familiarity with extended reality technologies. However, a statistically significant association was observed between gender and XR familiarity, with a p-value of 0.034. In this case, women were slightly underrepresented among those who indicated being familiar with XR, with 39 women identified in this group compared to an expected count of 43. In contrast, men were overrepresented, with 13 respondents reporting familiarity versus an expected 10.5.

Despite the low familiarity with the term "Extended Reality (XR)", awareness of individual technologies within it was visibly higher (Figure 5.3). Specifically, VR and AR were more familiar to students, with 211 respondents (93.36%) and 127 respondents (56.19%) reporting knowledge of these terms, respectively. MR remained as the least recognized one, with 17 respondents (7.52%) stating familiarity.

Q5 - Knowledge of XR Technologies

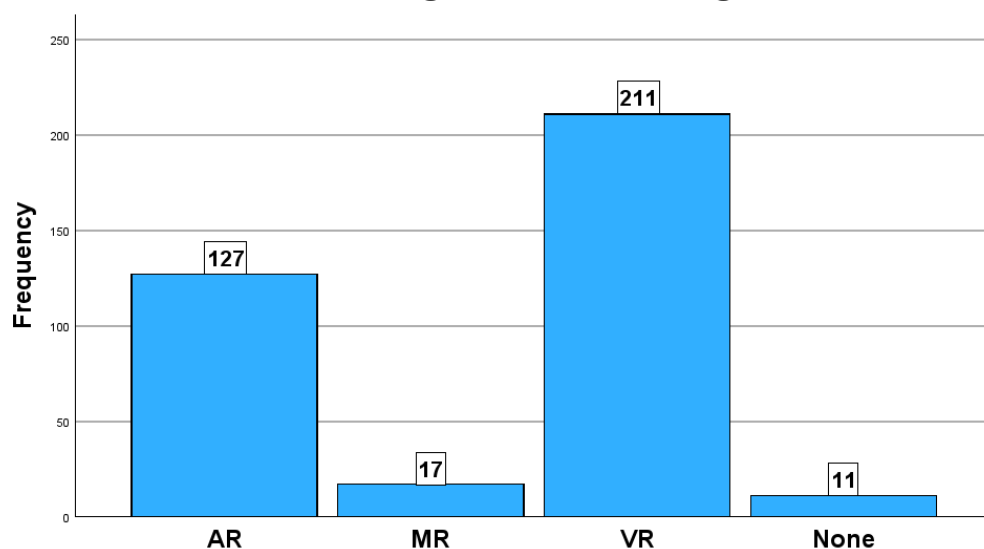


Figure 5.3: Self-reported awareness of XR's component technologies.

Regarding age, gender, and year of study, no associations were found with students' preference for AR, VR, or the option of not choosing any XR modality. Similarly, no significant associations were found between the selection of MR in relation to age or study year.

Despite this, gender was found to be significantly associated with the selection of MR as a familiar or preferred XR modality, with a p-value of 0.009. Given this, male participants were more likely to report familiarity with MR (7 vs. 3.3). In contrast, female participants were less likely to report familiarity with MR (9 vs. 13.5).

Nonetheless, a majority of students (n=129, 57.08%) reported that they were unable to distinguish between the three primary XR modalities (AR, MR, and VR), whereas 42.92% (n=97) indicated they could (Figure 5.4).

Q6- Ability to Distinguish XR Technologies

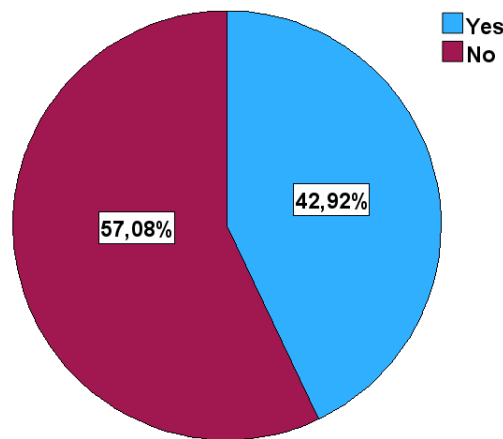


Figure 5.4: Reported ability to differentiate between AR, MR, and VR.

Students' ability to distinguish between XR technologies did not differ significantly by age ($p=0.848$), gender ($p=0.809$), or XR familiarity ($p=0.228$).

However, a significant association was observed across years of study ($p=0.048$). 1st year and 3rd year students were more likely than expected to report being able to distinguish XR types (9 vs. 6.0 and 17 vs. 12.0, respectively). In contrast, 2nd year students were less likely than expected to report this ability (39 vs 48.5). While the remaining years aligned more closely with expected values, 5th year students also slightly exceeded expectations (17 vs. 14.6).

A summary table on student's XR knowledge can be consulted below in Table 5.2.

Table 5.2: Students' XR knowledge summary table.

Variable	Category	n	%
XR Familiarity	Yes	54	23.90
	No	172	76.10

Variable	Category	n	%
Known XR Technologies	Augmented Reality (AR)	127	56.19
	Mixed Reality (MR)	17	7.52
	Virtual Reality (VR)	211	93.36
	None	11	4.87
Distinguish XR Technologies	Yes	97	42.92
	No	129	57.08

When it comes to the actual use of XR (Figure 5.5a), experience was limited with only 49 respondents (21.68%) stating having ever used any form of XR technology, given that the majority of students (n=177, 78.32%) had never had previously interacted with XR technologies. Among experienced students, three contexts in which they had used XR were explored (Figure 5.5b): games (n=29, 59.18%), studies/profession (n=11, 22.45%), and others (n=9, 18.37%).

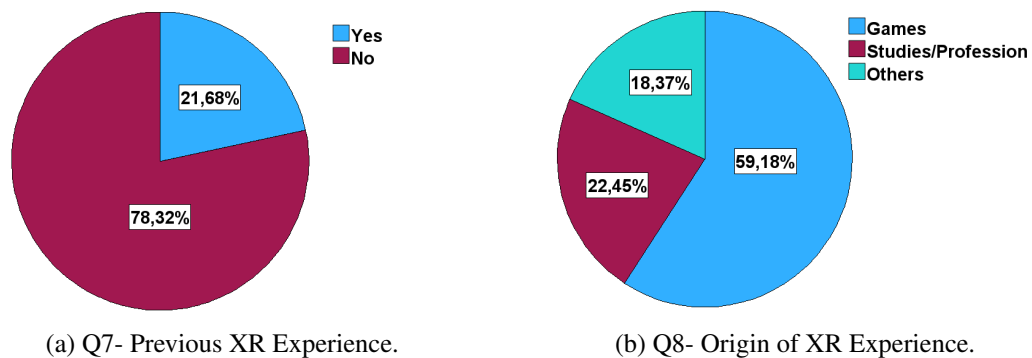


Figure 5.5: Reported XR experience and context of XR use.

Prior XR use varied significantly by gender ($p=0.047$), with males being more likely than expected to have used XR (11 vs. 9.5), and females slightly less likely than expected (36 vs. 39.0). However, XR experience did not differ significantly by age ($p=0.530$) or year of study ($p=0.097$). There was also a strong association between XR familiarity and XR experience ($p<0.001$). Respondents who reported being familiar with XR were much more likely than expected to have actual XR experience (22 vs. 11.7), while those unfamiliar with XR were less likely than expected to report prior use (27 vs. 37.3).

A similar pattern was observed regarding the ability to distinguish between XR technologies ($p<0.001$). Participants with XR experience were significantly more likely than expected to report being able to distinguish XR types (36 vs. 21), whereas those without XR experience were less likely than expected to report this ability (13 vs. 28). No significant associations were found

between the origin of XR experience and variables such as age, gender, study year, XR familiarity, ability to distinguish XR types, or XR experience.

A summary of statistics for XR prior experience is presented in Table 5.3.

Table 5.3: XR prior experience summary table.

Variable	Category	n	%
Distinguish XR Technologies	Yes	54	23.90
	No	129	57.08
XR Experience	Yes	49	21.68
	No	177	78.32
Area of Contact With XR	Games	29	59.18
	Studies/Profession	11	22.45
	Other	9	18.37

5.3 Perceived Utility and Format Preferences

After providing insights on their knowledge of XR technologies and previous encounters with them, students were asked whether they believed XR has a role to play in medical education and how they would prefer it to be implemented.

A large majority of participants agreed with the idea that XR could be a useful tool in medical education. Specifically, 211 out of 226 respondents (93.36%) agreed that XR technologies could be useful in medical education, while only 15 participants (6.64%) disagreed with the statement (Figure 5.6).

9- Successful XR Integration

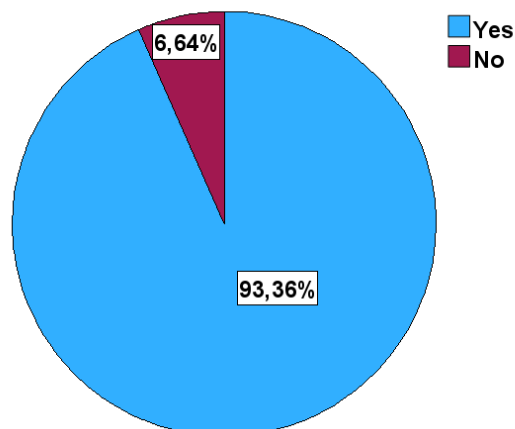


Figure 5.6: Perceptions distribution on the successful integration of XR.

No significant association was found between students' belief in XR's usefulness and age group ($p=0.859$), gender ($p=0.137$), or year of study ($p=0.586$). Similarly, neither prior familiarity with XR ($p=1.000$) nor previous XR experience ($p=0.201$) had a significant influence.

To explore which subject areas students considered most appropriate for XR use, respondents selected specific disciplines from clinical domains (Figure 5.7). The most favored course was surgery with 93.36% ($n=211$) of students choosing it as a course with high potential for the utilization of XR. Following it, radiology ($n=119$, 52.65%), emergency medicine ($n=115$, 50.88%), neurology ($n=108$, 47.79%), and forensic medicine ($n=99$, 43.81%) were also highly selected options. Less frequently mentioned courses included palliative medicine ($n=34$, 15.04%), pharmacology ($n=34$, 15.04%), microbiology ($n=32$, 14.16%), and infectiology ($n=30$, 13.27%).

Q10- Student's Clinical Subject Preferences for XR

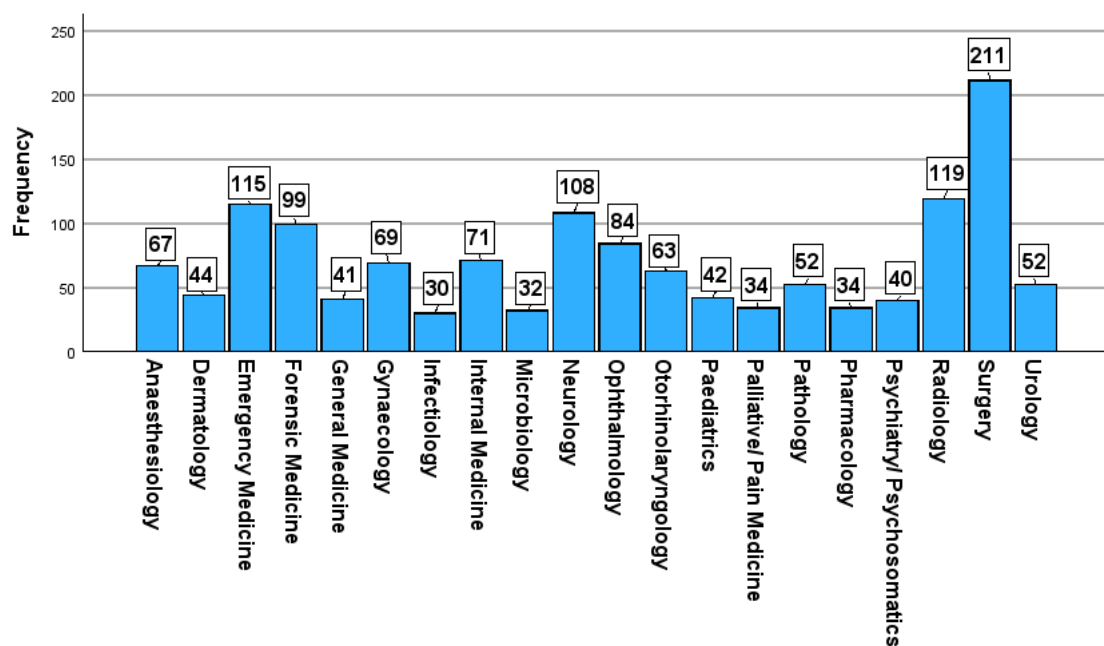


Figure 5.7: Preferred clinical disciplines for XR integration.

Tests showed statistically significant associations between certain discipline preferences and participants' age group, year of study, and XR integration.

Age group was significantly associated with preferences for Anesthesiology ($p<0.001$), Gynecology ($p=0.031$), Emergency Medicine ($p<0.001$), Forensic Medicine ($p=0.001$), and Microbiology ($p=0.041$). In Anesthesiology, the 21–25 age group was overrepresented (38 vs. 24.6), while the 18–20 group was underrepresented (24 vs. 37.9). Similar patterns appeared in Emergency Medicine with 56 vs. 42.2 for the 21–25 group; 51 vs. 65.1 for the 18–20 group. In Gynecology, the 21–25 group was also overrepresented (34 vs. 25.3), and the 18–20 group underrepresented

(31 vs. 39.1). Small overrepresentations were observed in the 31–35 group for Gynecology (2 vs. 0.9) and Microbiology (2 vs. 0.4). No students aged 26–30 or over 35 selected Forensic Medicine, despite expected counts above zero.

Year of study was associated with preferences for Anesthesiology ($p=0.009$), Gynecology ($p=0.019$), Emergency Medicine ($p=0.007$), and Urology ($p=0.019$). 1st year students were underrepresented in Anesthesiology (1 vs. 4.2) and Emergency Medicine (4 vs. 7.1), while students in the 4th (15 vs. 9.5 and 21 vs. 16.3, respectively) and 5th (14 vs. 10.1 and 25 vs. 17.3, respectively) years were overrepresented across these fields. Urology interest peaked in the 5th year (16 vs. 7.8), and 2nd year students were underrepresented (19 vs. 26). In Gynecology, 4th year students matched expected values exactly (16/16), while 1st (2 vs. 4.3) and 2nd (27 vs. 34.5) years selected it less than expected.

There was also a significant association between belief in successful XR integration and interest in Surgery ($p=0.011$). Among students who didn't believe in successful XR integration, 11 of 15 selected Surgery. Among those who did believe in XR integration, 200 of 211 (94.79%) selected Surgery. No significant associations were found between discipline preferences and XR familiarity, prior XR experience, or context of XR use.

Regarding preclinical specialties (Figure 5.8), Anatomy had the majority of the votes with 198 (87.61%). Physiology (n=128, 56.64%) was in second place, and Terminology (n=120, 53.10%) a close third. The least selected options were Biochemistry with 33 votes (14.60%), and Biology and Psychology/Sociology, both with 22 votes (9.73%).

Q11- Student's Preference on Preclinical Subjects for XR Use

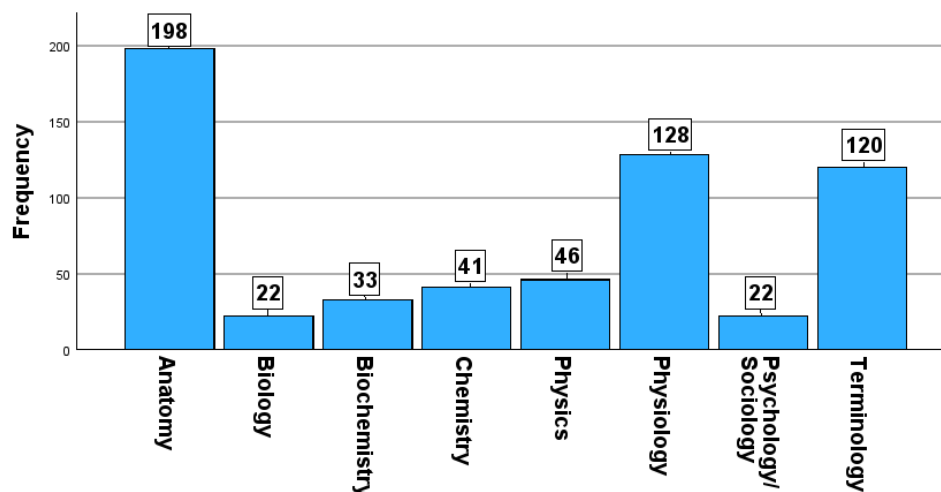


Figure 5.8: Student's preclinical disciplines choices for XR integration.

Associations between preferences and participant characteristics varied across variables. No associations were found between age group and any of the preclinical discipline preferences. A weak to moderate association was observed between gender and interest in anatomy ($p=0.046$).

Male students showed greater interest in anatomy than expected (43 vs. 38.5), while female students had a more balanced distribution, with 153 expressing interest and 27 not interested, slightly lower than expected (153 vs. 157.7).

An association was also found between year of study and preference for physiology ($p=0.045$). 1st year students showed slightly less interest than expected, (6 vs. 7.9) and 2nd year students showed greater interest (72 vs. 64). Other years followed expected distributions, except for 6th year students, none of whom selected Physiology. Although the 6th year group was small ($n = 5$), their complete absence contributed to the significance.

Finally, an association was found between the variables year of study and preference for terminology ($p=0.026$). 3rd year students showed more interest than expected (21 vs. 14.9), while 1st year and 5th year students selected it less often than anticipated (4 vs. 7.4, and 13 vs. 18.1, respectively). There were no significant associations found between preference for any clinical specialty and students' ability to differentiate XR types, previous exposure to XR, the origin of their XR exposure, or their perception of the usefulness of XR integration.

On the subject of preferred instructional formats for XR use (Figure 5.9a), students identified practical classes as the most relevant for XR integration ($n=187$, 82.74%). This was followed by seminars ($n=29$, 12.83%), and finally by theoretical classes ($n=10$, 4.42%). For evaluation formats (Figure 5.9b), the overwhelming majority ($n=218$, 96.46%) of respondents chose practical exams as the best choice for XR integration, while only 8 respondents (3.54%) disagreed and chose theoretical exams.

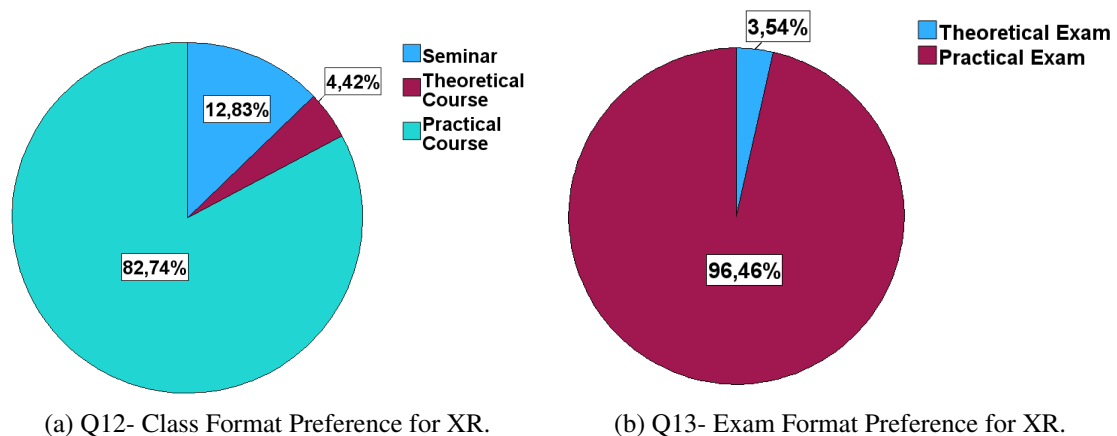


Figure 5.9: XR integration preferences in teaching and evaluation formats

No significant associations were found between teaching or evaluation format preferences and any of the following: age, gender, year of study, XR familiarity, ability to distinguish XR types, prior XR experience, or context of XR use. However, an exception was observed for the relationship between XR integration perception and teaching format ($p=0.036$), where students who reported that XR integration would not be useful showed higher-than-expected preferences for seminars (4 vs. 1.9) and theoretical classes (2 vs. 0.7), and those who saw XR as useful

selected practical classes more often than expected (178 vs. 174.6). Additionally, no association was found between XR integration perception and evaluation format.

A breakdown of the number of cases and frequencies for mentioned variables is presented in the table below (Table 5.4).

Table 5.4: Useful integration of XR in medical education, clinical and preclinical specialties, and class and evaluation format preferences for XR integration, a summary table.

Variable	Category	n	%
Useful Integration of XR in Medical Education	Yes	211	93.36
	No	15	6.64
Clinical Specialties for XR Integration	Anesthesiology	67	29.65
	Dermatology	44	19.47
	Emergency Medicine	115	50.88
	Forensic Medicine	99	43.81
	General Medicine	41	18.14
	Gynecology	69	30.53
	Infectiology	30	13.27
	Internal Medicine	71	31.42
	Microbiology	32	14.16
	Neurology	108	47.79
	Ophthalmology	84	37.17
	Otorhinolaryngology	63	27.88
	Palliative Medicine	34	15.04
	Pathology	52	23.01
	Pharmacology	34	15.04
	Pediatrics	42	18.58
	Psychiatry/Psychosomatics	40	17.70
	Radiology	119	52.65
	Surgery	211	93.36
	Urology	52	23.01
Preclinical Specialties for XR Integration	Anatomy	198	87.61
	Biology	22	9.73
	Biochemistry	33	14.60
	Physics	46	20.35
	Physiology	128	56.64
	Psychology/Sociology	22	9.73
	Chemistry	41	18.14
	Terminology	120	53.10

Variable	Category	n	%
Class Format Preference for XR Integration	Seminar	29	12.83
	Theoretical Class	10	4.42
	Practical Class	187	82.79
Exam Format Preferences for the Integration of XR	Theoretical Exam	8	3.54
	Practical Exam	218	96.46

5.4 Opportunities and Challenges of XR in Medical Education

Main potential advantages and disadvantages of integrating XR into medical education were also assessed (Figure 5.10). The top three chosen advantages were broad simulation possibilities (n=209, 92.48%), closely followed by interactive first-person learning (n=186, 82.30%), and competence improvements (n=166, 73.45%). The options of depiction of rare decisions (n=92, 40.71%) and repeatable scenarios (n=95, 42.04%) were less chosen, each with under 100 votes. Consequently, overall students only saw advantages on the integration of XR into their education, as "No Advantages" was only chosen three times (1.33%).

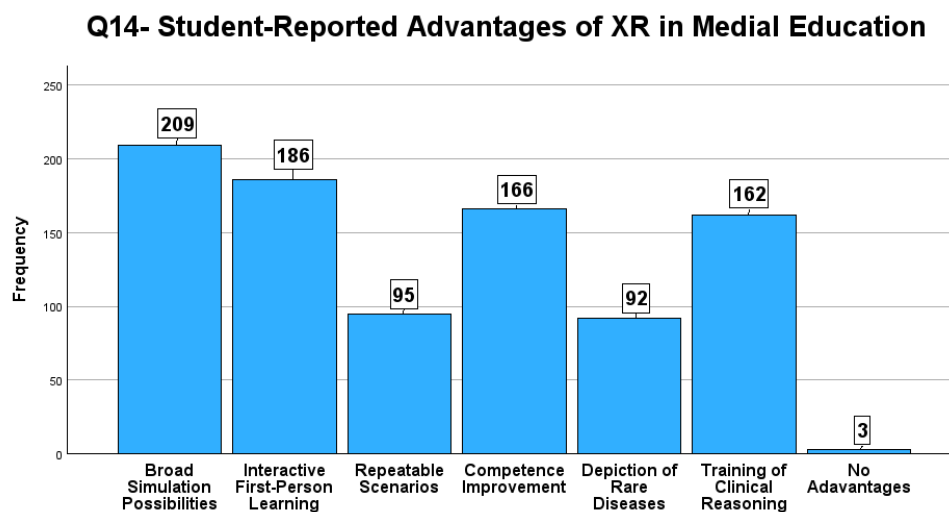


Figure 5.10: Advantages of XR in medical education as reported by students.

Associations between perceived advantages and participant characteristics were examined, showing no significant relationships for age, gender, XR familiarity, prior XR experience, or preferred teaching format. A significant association was found between year of study and the benefit "Representation of Rare Diseases" ($p=0.020$): 3rd year students were more likely than expected to agree (17 vs. 11.4) and less likely to disagree (11 vs. 16.6); 4th year students also agreed more often than expected (17 vs. 13.0) and disagreed less often (15 vs. 19.0); 5th year students were less likely than expected to agree (9 vs. 13.8) and more likely to disagree (25 vs. 20.2).

Ability to distinguish VR, AR, and MR was significantly associated with "Broad Simulation Possibilities" ($p=0.029$): students who could distinguish these modalities agreed more often than

expected (94 vs. 89.7) and disagreed less often (3 vs. 7.3), whereas those who could not distinguish them agreed less often than expected (115 vs. 119.3) and disagreed more often (14 vs. 9.7). The same ability was also associated with “Improvement of Competencies” ($p=0.018$): distinguishers agreed more often than expected (79 vs. 71.2) and disagreed less often (18 vs. 25.8), while non-distinguishers disagreed more often than expected (42 vs. 34.2) and agreed less often (87 vs. 94.8).

Origin of XR experience showed a significant association with “Repeatable Scenarios”, earning a p -value of 0.019: students with experience from studies or profession agreed less often than expected (1 vs. 4.7) and disagreed more often (10 vs. 6.3); those with gaming experience agreed slightly more than expected (14 vs. 12.4) and disagreed less (15 vs. 16.6).

Perception of successful XR integration was associated with “Broad Simulation Possibilities” ($p=0.018$): those who did not see XR as successfully integrated agreed less often than expected (4 vs. 13.9) and disagreed more often (11 vs. 1.1); those who did see it as integrated agreed slightly more than expected (198 vs. 195.1) and disagreed less (13 vs. 15.9). It was also associated with “Training of Clinical Reasoning” ($p=0.014$): students who did not perceive successful integration agreed less often than expected (6 vs. 10.8) and disagreed more often (9 vs. 4.2), whereas those who did agree more often than expected (156 vs. 151.2) and disagreed less (55 vs. 59.8).

Finally, evaluation format showed a significant association with “Improvement of Competencies” ($p=0.033$): students preferring XR on theoretical exams disagreed more often than expected (5 vs. 2.1) and agreed less (3 vs. 5.9), while those preferring XR on practical exams agreed more often than expected (163 vs. 160.1) and disagreed less (55 vs. 57.9).

Turning to concerns (Figure 5.11), “Technical Error Susceptibility” topped the list with 141 students (62.39%) choosing it as their main reason for distrust in XR. “Technical Requirements/Competences” was next ($n=109$, 48.23%), followed by “Health Problems” ($n=74$, 32.74%) and “Unrealistic Experience” ($n=64$, 28.32%). A minority of 15 students (6.64%) reported no disadvantages.

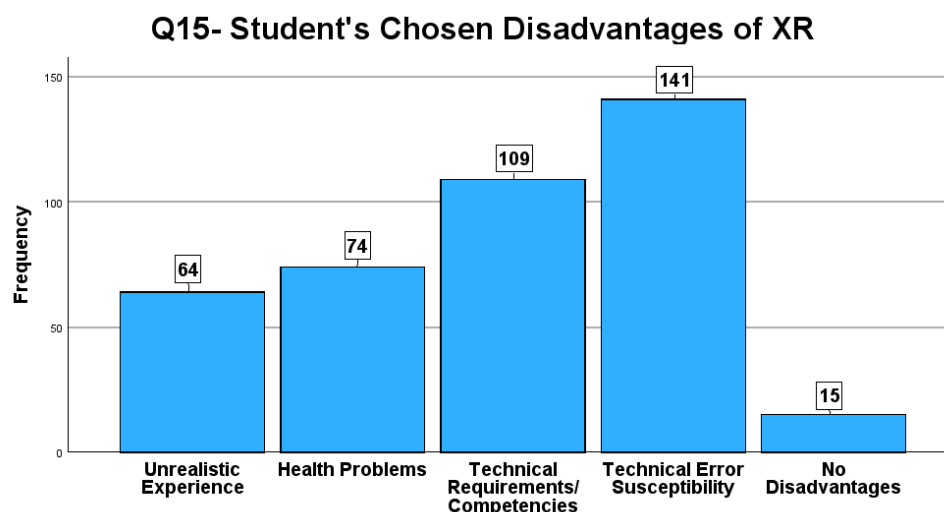


Figure 5.11: Student's reported disadvantages of XR technologies.

Associations between the selection of XR-related drawbacks and participant characteristics were largely non-significant. No associations were found between any of the listed disadvantages and gender, year of study, XR familiarity, ability to distinguish XR types, prior XR experience, origin of XR experience, or perceived success of XR integration.

However, a significant association was found between age group and the perceived disadvantage “technical errors or malfunctions” ($p=0.011$). Among students aged 18–20, more than expected selected this drawback (89 vs. 79.9), and fewer than expected did not (39 vs. 48.1). Students aged 21–25 showed a slight deviation in the opposite direction, selecting the item less often than expected (47 vs. 51.8) and not selecting it more often than expected (36 vs. 31.2).

Below, Table 5.5 summarizes the number of responses and corresponding frequencies for each of the listed advantages and disadvantages of XR technologies reported by the participants.

Table 5.5: Distribution of responses related to XR advantages and disadvantages.

Variable	Category	n	%
Advantages of XR	Broad simulation possibilities	209	92.48
	Repeatable scenarios	95	42.04
	Depiction of rare diseases	92	40.71
	Interactive first-person learning	186	82.30
	Training of clinical reasoning	162	71.68
	Competence improvement	166	73.45
	No advantages	3	1.33
Disadvantages of XR	Health problems	74	32.74
	Technical requirements/competences	109	48.23
	Technical error susceptibility	141	62.39
	Unrealistic experience	64	28.32
	No disadvantages	15	6.64

5.5 Attitudes Towards XR in Medical Education

In the final set of close-ended items, participants were asked to express their overall attitudes toward XR in medical education on several subquestions using a 5-point Likert scale (1="Definitely Not" to 5="Definitely Yes") (Figure 5.12). The nine statements addressed perceptions of XR's benefits, potential curricular integration, and the imagined application of XR to various clinical activities.

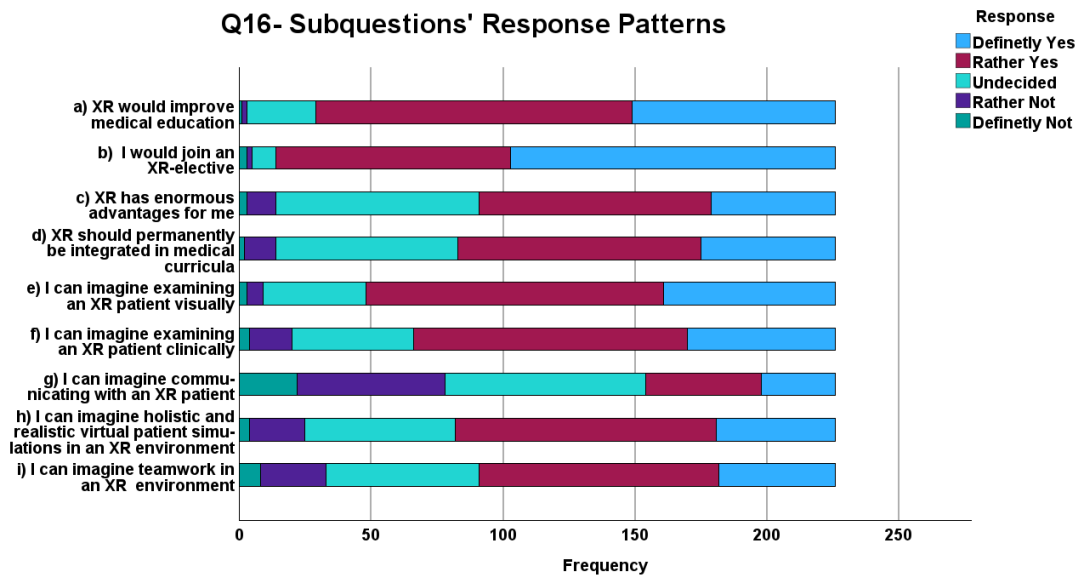


Figure 5.12: Distribution of responses across survey items rated on a 5-point Likert scale.

Overall, agreement levels were high for most items, particularly those on XR's educational value and students' willingness to engage with XR-based instruction.

A total of 197 students (87.17%) responded "Rather Yes" or "Definitely Yes" to the statement that XR would improve medical education, while only 3 students (1.33%) disagreed, and 26 (11.50%) remained undecided. Similarly, 212 participants (93.81%) expressed interest in joining a course using XR, with only 5 students (2.21%) expressing disagreement.

Statements concerning imagined XR applications in clinical scenarios showed more varied responses. The ability to imagine visual or clinical examinations of patients in XR environments was affirmed by 178 students (78.76%) and 160 students (70.80%), respectively. However, perceived viability declined for more complex interactions. For example, 78 participants (34.51%) expressed agreement that communication with XR patients was imaginable, while a relatively large number (78.76%) responded "Undecided" or selected disagreement options.

Similar trends were observed in items addressing holistic simulations and teamwork scenarios, with 144 students (63.72%) agreeing with the idea of working in XR teams, and 144 (63.72%) also endorsing the potential for holistic virtual simulations, as detailed in Table 5.6.

Table 5.6: Distribution of participant's responses to each of Q16's subquestions.

Variable	Definitely Not	Rather Not	Undecided	Rather Yes	Definitely Yes
a) XR would improve medical education	1	2	26	120	77
b) I would join an XR-elective	3	2	9	89	123

Variable	Definitely Not	Rather Not	Undecided	Rather Yes	Definitely Yes
c) XR has enormous advantages for me	3	11	77	88	47
d) XR should permanently be integrated in medical curricula	2	12	69	92	51
e) I can imagine examining an XR patient visually	3	6	39	113	65
f) I can imagine examining an XR patient clinically	4	16	46	104	56
g) I can imagine communicating with an XR patient	22	56	76	44	28
h) I can imagine holistic and realistic virtual patient simulations in an XR environment	4	21	57	99	45
i) I can imagine teamwork in an XR environment	8	25	58	97	44

Statistical analyses were conducted to examine whether responses to the subitems of Question 16 were associated with participants' demographic or experiential characteristics. No significant associations were found between any of the subitems and age group, XR familiarity, ability to distinguish XR types, prior XR experience, or origin of XR experience. However, several significant associations emerged for other variables.

Gender was significantly associated with responses to item a) "XR would improve medical education" ($p=0.029$). Female students were more likely than expected to agree (161 vs. 156.9), while being slightly less likely to be undecided (17 vs. 20.7) or disagree (2 vs. 2.4). Male students, in contrast, showed slightly lower-than-expected agreement (35 vs. 38.4) and a higher rate of uncertainty (9 vs. 5.1). For item i) "I can imagine teamwork in an XR environment" ($p=0.039$), male respondents were more likely to select "Definitely Yes" (12 vs. 8.6) and less likely to choose "Rather Yes" (15 vs. 17.7), while female respondents leaned more towards "Rather Yes" (76 vs. 72.5) and slightly under-selected "Definitely Yes" (32 vs. 35.0). Both genders showed undecided responses close to expectations.

Year of study showed significant associations with two items. For item b) "I would join an XR-elective" ($p=0.041$), 1st year students over-selected "Definitely Yes" (11 vs. 7.6) and slightly over-selected "Definitely Not" (1 vs. 0.2). 2nd year students were more likely to be undecided (6 vs. 4.5), and 4th year students were overrepresented in "Rather Not" (2 vs. 0.3) despite otherwise higher "Yes" responses. 6th year students showed low endorsement overall, including one "Definitely Not." For item c) "XR has enormous advantages for me" ($p=0.017$), 1st year students over-selected both "Rather Yes" (7 vs. 5.5) and "Rather Not" (3 vs. 0.7), while under-selecting

“Undecided” (1 vs. 4.8). 2nd year students were overrepresented in “Undecided” (44 vs. 38.5) and underrepresented in “Rather Not” (1 vs. 5.5). 4th year students chose “Rather Not” (4 vs. 1.6) and “Definitely Yes” (8 vs. 6.7) more often than expected. 5th year students aligned closely with expected values, with mild increases in “Rather Not” (2 vs. 1.7) and “Definitely Yes” (8 vs. 7.1). 6th year responses were polarized, with elevated “Definitely Not” (1 vs. 0.1) and “Definitely Yes” (2 vs. 1.0), and fewer mid-scale responses.

A strong association was also observed between responses to item a) and perceived success of XR integration in education ($p < 0.001$). Among students who did not perceive XR as potentially being successfully integrated, “Rather Not” (2 vs. 0.1) and “Undecided” (5 vs. 1.7) were over-selected, while “Rather Yes” was under-selected (3 vs. 8.0). Among those who did perceive a possible successful integration, “Rather Yes” was selected more than expected (117 vs. 112.0), “Definitely Yes” closely matched expectations (72 vs. 71.9), and negative or uncertain responses were slightly underrepresented.

Responses to multiple items were significantly associated with students’ preferred class format for XR instruction. In general, students favoring practical classes were more likely to select “Definitely Yes” across several items: item a) (69 vs. 63.7), item b) (107 vs. 101.8), item c) (44 vs. 38.9), item e) (62 vs. 53.8), item f) (53 vs. 46.3), item h) (42 vs. 37.2), and item i) (41 vs. 36.4). In contrast, those preferring seminar or theoretical classes tended to be more uncertain or less emphatic. For instance, theoretical class supporters were overrepresented in “Undecided” responses for item a) (6 vs. 1.2), item c) (9 vs. 3.4), and item h) (4 vs. 2.5), and underrepresented in strong agreement, including complete absence in “Definitely Yes” for several items: item a) 0 vs. 3.4, h) 0 vs. 2.0. Seminar-preferring students were often overrepresented in mid-scale options such as “Rather Yes” or “Rather Not”: item h) with “Rather Not” at 7 vs. 2.7; item e) with “Rather Yes” at 19 vs. 14.5.

A similar pattern was found for preferred evaluation format. Students who favored practical exams selected strong agreement more frequently, especially in item a), where 118 chose “Rather Yes” and 76 “Definitely Yes” (values close to expectation), while theoretical exam supporters over-selected “Undecided” (5 vs. 0.9) and under-selected both “Rather Yes” and “Definitely Yes.” For item b) ($p = 0.003$), theoretical exam supporters were again overrepresented in “Rather Not” (1 vs. 0.1) and “Undecided” (2 vs. 0.3), and underrepresented in “Definitely Yes” (1 vs. 4.4). Practical exam supporters again closely matched expectations, with 207 participants selecting either “Rather Yes” or “Definitely Yes” (vs. expected 204.4).

Having given their opinion on the current educational value and integration of XR, students were then asked to estimate how likely they believed XR technologies were to influence the future of medical education. Using a scale from 0 (“Very Unlikely”) to 10 (“Very Likely”), participants expressed generally optimistic expectations.

The distribution was asymmetrical, with many participants expressing high confidence (Figure 5.13). The most frequent ratings were 8 (32.3%), 7 (22.6%), 10 (15.9%), and 9 (14.6%). Ratings below 5 were rare, with only 1 participant (0.4%) rating a 3, and small percentages selecting 4 (2.2%) or 5 (2.7%). The cumulative percentage of ratings 7 or above reached 84.1%.

Q17- Likelihood of XR Influencing The Future of Medical Education

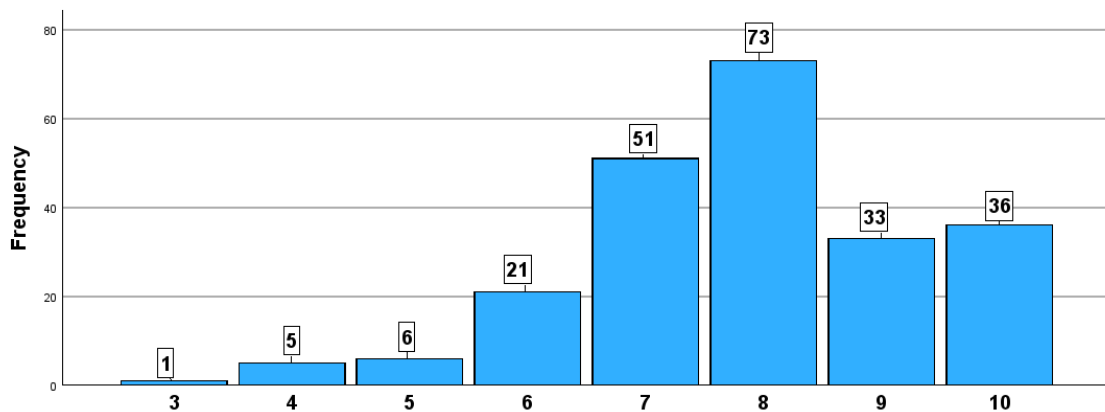


Figure 5.13: Frequency distribution of participant ratings on the likelihood that XR technologies will influence the future of medical education, measured on a 0 (Very Unlikely) to 10 (Very Likely) scale.

No associations were found between perceived future impact of XR and participant age, gender, year of study, XR familiarity, ability to distinguish XR technologies, prior XR experience, origin of XR experience, or evaluation format. Despite this, significant associations were found with two variables related to XR integration ($p = 0.002$) and class format ($p = 0.042$).

Participants reporting no successful XR integration were overrepresented at rating 7 (7 vs. 3.4) but underrepresented at ratings 8 and 9 (1 vs. 4.8, and 0 vs. 2.2, respectively). Conversely, participants reporting successful XR integration were overrepresented at higher ratings of 8 and 9 (72 vs. 68.2, and 33 vs. 30.8) and underrepresented at rating 7 (44 vs. 47.6).

Regarding class format, participants who chose seminar showed higher-than-expected frequencies at mid-range ratings 6 (6 vs. 2.7) and 7 (10 vs. 6.5), but were underrepresented at high-end ratings 8–10. Those that chose theoretical class were overrepresented at ratings 5 (1 vs. 0.3) and 6 (3 vs. 0.9), yet recorded no responses at ratings 7 and 10. Those that preferred practical classes for XR were overrepresented at top ratings 8 (63 vs. 60.4) and 10 (34 vs. 29.8), while underrepresented at rating 6 (12 vs. 17.4).

The distribution of participant ratings for the perceived future impact of XR is presented in Table 5.7.

Table 5.7: Distribution of participant ratings on the likelihood that XR will influence the future of medical education (Q17, scale 0–10).

Rating	n	%
1	0	0
2	0	0
3	1	0.44

Rating	n	%
4	5	2.21
5	6	2.65
6	21	9.29
7	51	22.57
8	73	32.30
9	33	14.60
10	36	15.93

5.6 Proposed XR Scenarios in Medical Education

The survey's final question invited participants to suggest XR scenarios they would like to see developed for medical education. Out of the total respondents, 32 provided answers ranging from single words to short phrases, with the most common words being summarized in Figure 5.14.



Figure 5.14: Word cloud illustrating key terms from participant suggestions for XR-based scenarios in medical education.

A large number of responses centered around surgical training. Participants expressed interest in simulated operating room environments, surgical procedures, and technical practice. These suggestions often referred to the possibility of rehearsing complex surgeries and engaging with realistic clinical settings, highlighting surgery as a primary application for XR. Emergency medicine was another commonly mentioned area. Students identified the value of XR for simulating urgent care situations, allowing for experiential learning in scenarios that require quick thinking and decision-making under pressure.

Several participants mentioned clinical training uses beyond surgery and emergency care. These included ideas related to patient consultations, clinical case simulations, and procedural practice. Specific procedures, including punctures and blood gas analysis, were named as examples of tasks that could be rehearsed using XR tools. A smaller set of responses touched on the role of XR in supporting early exposure to practical skills or enhancing self-guided study in the absence of physical materials. Additionally, one or two participants pointed out limitations of XR, expressing concern about its inability to replicate real patient interaction, especially for learning aspects that involve communication or empathy.

On the preclinical side, anatomy emerged as a significant area of interest, particularly in relation to the visualization of complex structures. Participants highlighted the potential of XR to support anatomical learning by offering detailed, three-dimensional views of internal systems that are difficult to fully explore through traditional methods. This included references to the study of organs, vessels, nerves, and bones. Some respondents also suggested disciplines such as biochemistry, pharmacology, and physiology. In these cases, XR was seen as a way to better visualize dynamic or abstract content, such as molecular interactions and physiological mechanisms.

Chapter 6

Discussion

This chapter is dedicated to the interpretation of the findings presented in Chapter 5.

The discussion begins with a comparative analysis between the present study and the work from which the original survey was adapted. This serves to highlight both consistencies and discrepancies across different academic and cultural settings. Following this, the chapter explores what the responses reveal about the current landscape and future possibilities for the integration of XR technologies into medical education.

6.1 Comparison to Previous Research

To contextualize the results obtained from the present study, a comparison with the results from the study conducted by Mergen *et al.* is called for. This comparison allows for the identification of patterns that are consistent across different academical and cultural environments, as well as divergences that may reflect either institutional, regional, or cohort-specific dynamics.

6.1.1 Demographics and Previous VR/XR Experience

Several parallels as well as divergences were found when comparing the demographic profiles and prior exposure to VR/XR between the current sample and that of Mergen *et al.*. Both studies recruited substantial proportions of their respective medical student populations, with 14.5% participation at Saarland university in Mergen's study and 20.75% participation at ICBAS in the present one.

In Mergen's study, approximately 50.4% of students were enrolled in the preclinical phase, and 2.9% were in the final practical year. In the present study, which targeted undergraduate students, the distribution was across all six years of the the curriculum, with the highest proportion in the second year (50.00%) and the smallest in the sixth year (2.21%).

In terms of gender distribution, both samples were predominantly female. In the present study, 79.56% of respondents identified as female, while 19.47% identified as male. Similarly, Mergen *et al.* reported a sample that was 65.48% female and 34.52% male. In both studies, a significant gender-based disparity in previous experience with immersive technologies was evident. Starting

with Mergen, only 23.0% of female students reported prior VR experience compared to 50.6% of male students ($p < 0.001$). Likewise, the present study found a significant association between gender and XR experience ($p = 0.047$), with males (29.55%) being more likely than expected to have used XR technologies and females (21.67%) slightly less likely.

Age distribution also showed some alignment, although with different emphasis. In the present study, a large majority of respondents were younger students: 56.64% were aged 18–20 and 36.73% were 21–25, with only 6.63% over 25 years of age. In Mergen's study, the largest group fell within the 21–25 range (54.37%), followed by 18–20 (26.19%), while older age brackets made up 19.44% combined. Despite differences in the specific proportions, both studies found that age and previous immersive technology had no significant association.

Finally, when it comes to overall experience with immersive technologies, both cohorts displayed limited exposure. In Mergen's study, 67.5% of students had no prior VR experience, with males more likely to have previous experience, as well as preclinical students. In the present study, the number of students with no prior XR experience was even higher, coming in at 78.32%. In the same manner, males were more likely to have prior XR experience, along with students with knowledge of the concept of XR. Among those with experience, both studies identified gaming as the most common context: 74.4% in Mergen and 59.18% in the present study. In the same manner, both studies found that professional or educational use was less frequent: 22.45% in the present study and 25.6% in Mergen's, with females more inclined toward this category. In summary, both studies reveal similar patterns, such as female-majority samples with significantly lower immersive technology experience among women, low overall exposure to VR/XR technologies, and a strong gender-based disparity in usage patterns. Age and academic stage did not consistently influence experience across studies, although a relationship with gender and study progress was detected in Mergen's data alone.

6.1.2 Integration of VR/XR into Medical Curricula

The next aspect explored was the medical students' perceptions regarding the inclusion of immersive technologies in medical education.

In the present study, 93.36% of students supported the integration of XR into medical education, closely mirroring the 95.2% support stated by Mergen *et al.* for VR. Neither study identified statistically significant differences in support for VR/XR integration based on demographic or experiential variables. In Mergen's study, no significant associations were found with gender, prior VR experience, age group, or study progress. Likewise, the present study found no significant differences based on gender, age, year of study, XR familiarity, or previous XR experience.

When asked about preferred class formats for implementing immersive technologies, practical classes were clearly favored in both studies. In the current study, 82.74% of participants preferred practical classes, followed by seminars (12.83%) and theoretical classes (4.42%). Mergen *et al.* reported a similar trend, with 48.3% of students preferring practical course, also followed by seminars (30.0%), then clinical examination courses (17.5%), and lectures (4.2%). Although the proportions differ, both cohorts overwhelmingly supported hands-on formats over passive or

lecture-based ones. Additionally, a significant relationship was observed in the present study between students' belief in the usefulness of XR and their preferred instructional format. Students who supported XR integration favored practical classes more than expected, while those who did not were more inclined to select seminars and theoretical classes.

In sum, both studies demonstrate widespread support for the curricular integration of immersive technologies and a shared preference for practical teaching formats. These findings suggest that students perceive XR and VR primarily as tools to enhance experiential learning rather than to augment traditional lecture-based instruction.

6.1.3 VR/XR Integration in Clinical Specialties

In both studies it was confirmed that medical students predominantly favored the integration of XR technologies into specific clinical specialties, with surgery being the most frequently selected area. In the present study, 93.36% of participants selected surgery as highly suitable for XR use, compared to 79.2% in Mergen's study. Emergency medicine also stood out in both datasets, with 50.88% of students selecting it in the present study and 60.0% in Mergen's. Additionally, radiology (52.65%), neurology (47.79%), and forensic medicine (43.811%) were among the more popular options in the current survey, whereas in Mergen et al.'s study, general medicine (55.0%) followed emergency medicine in popularity.

Mergen et al. reported that the average number of specialties selected per student was six, and, in their cohort, gender was significantly associated with preferences for dermatology, neurology, pediatrics, palliative medicine, psychiatry, and forensic medicine. Female students were more likely than males to select these specialties, with the exception of forensic medicine, where male students were overrepresented. Comparing to the present study, associations were found between specialty preferences and demographic variables. Age group was significantly associated with preferences for anesthesiology, gynecology, emergency medicine, forensic medicine, and microbiology. For example, students aged 21–25 were overrepresented in selections for anesthesiology and emergency medicine, whereas the 18–20 group was underrepresented in the same fields. Similarly, study year was associated with preferences for anesthesiology, gynecology, emergency medicine, and urology. Upper-year students tended to show greater interest in these specialties, particularly 4th and 5th year students. A significant association was also observed between students' belief in XR's usefulness and their selection of surgery: those who believed in XR integration selected surgery more frequently than expected, while among those who did not believe in XR's usefulness, a lower-than-expected number selected surgery.

In summary, both studies highlight surgery and emergency medicine as the most promising specialties for XR integration, suggesting a shared perception of XR's value in high-intensity, procedural domains. While Mergen's study revealed several gender-based differences in specialty preferences, the present study found more pronounced associations with age and year of study. Nonetheless, the consistent emphasis on hands-on and visually intensive fields underscores a common recognition among students of XR's potential to enhance experiential learning in clinical training.

6.1.4 VR/XR Integration in Preclinical Specialties

Anatomy was the top preclinical discipline selected for VR/XR integration in both studies. In the current study, 87.61% of participants selected anatomy, a result closely aligned with Mergen's findings, where 91.7% of students also favored its inclusion. Physiology was the second most frequently chosen option, with 56.64% in the present study and an unspecified but high proportion in Mergen's. However, while Mergen identified Psychology as the third most preferred preclinical subject overall (with students in the final year placing it ahead of physiology), students in the present study preferred Terminology as the third most promising area (53.10%), while Psychology/Sociology ranked among the least selected (9.73%).

In terms of associations, both studies reported no significant influence of age group on preferences for preclinical disciplines. Mergen also found no significant relationship with gender, whereas the present study identified a weak to moderate gender-based association in preferences for Anatomy, where male students showed slightly more interest in Anatomy than expected, while female responses closely matched the expected values. Year of study was also related to preferences in the current study: 2nd year students expressed more interest than expected in Physiology, while interest in Terminology was higher among 3rd year students and lower among 1st and 5th year students. On the contrary, no year-based associations were found in Mergen's results, where students across academic phases showed similar patterns. Neither study found meaningful associations between preferences for preclinical subjects and prior XR experience or familiarity.

Overall, both studies indicate Anatomy and Physiology as leading candidates for VR/XR integration in preclinical education, reflecting consensus on their foundational and visual nature. However, divergence appears in third-place preferences and in the presence of demographic influences.

6.1.5 Advantages of VR/XR

Strong enthusiasm for integration of VR/XR technologies in medical education was shown across both studies. Mergen reported that two-thirds of students ($n = 169$) believed VR had enormous advantages, and 86.1% thought VR could improve medical teaching. Similarly, in the present study, 87.17% of students agreed that XR would improve medical education, and only 1.33% disagreed, indicating comparable levels of optimism. A slightly higher percentage (93.81%) in the present study expressed interest in joining an XR course, compared to 86.5% in Mergen's sample.

When examining specific perceived advantages, both cohorts placed "broad simulation possibilities" at the top: 88.1% in Mergen vs. 92.48% in the present study. "Interactive first-person learning" was similarly well-rated (77.0% vs. 82.30%), followed by "improvement of competencies" (74.2% vs. 73.45%). However, differences emerged in how students valued other aspects. Mergen's cohort showed higher appreciation for repeatable usage (78.2% vs. 42.04%) and depiction of rare diseases (52.8% vs. 40.71%). In contrast, the present study revealed a much more

reserved view on these two features, as both were selected by fewer than half of respondents. Additionally, Mergen found that VR-naïve participants more often endorsed VR's advantages (74–78%) than those with prior experience (31–35%), while no such differentiation based on XR experience was observed in the current data. Only three students (1.33%) in the current study selected “No Advantages,” closely mirroring Mergen, where only one student rejected all advantages.

As for relevant factors, Mergen did not report any significant associations between perceived advantages and participant characteristics. In contrast, the current study identified several associations. For instance, year of study was significantly related to the perceived value of representing rare diseases, with 3rd and 4th year students agreeing more than expected, while 5th year students agreed less. Additionally, students who could distinguish between VR, AR, and MR were more likely to endorse “broad simulation possibilities” and “competency improvement”.

In summary, both studies demonstrate strong student support for the integration of VR/XR technologies into medical education, particularly in terms of their potential to enhance learning through immersive simulations and skill development. While both cohorts prioritized broad simulation possibilities and interactive learning, the present study found lower appreciation for repeatability and rare disease depiction. Moreover, unlike Mergen's findings, the present study identified significant associations between specific perceived advantages and student characteristics such as year of study and XR literacy.

6.1.6 Disadvantages of VR/XR

When examining the disadvantages of XR in medical education, both the current study and Mergen's findings highlight technical issues as the primary concern. In both datasets, “Technical Requirements or Competencies” and “Technical Error Susceptibility” were the most frequently cited drawbacks, with 48.23% and 62.39% of students in the current study selecting these, compared to 59.9% and 42.1% in Mergen's cohort, respectively. Health-related concerns were also similarly acknowledged (32.74% vs. 28.6% in Mergen), while “Unrealistic Scenarios” were selected by 28.32% of respondents, aligning closely with Mergen's 32.1%. However, a notable difference emerged in the proportion of students who saw no disadvantages, only 6.64% in the current sample compared to 12.7% in Mergen's.

While Mergen observed a significant association between prior VR experience and concern about health issues (more concern among experienced users), no such relationship was found in the current study. The only significant association identified in this dataset was between age and the concern of technical errors, specifically among the youngest cohort (18–20), which partially mirrors Mergen's observation that younger students expressed greater concern over technical malfunctions.

Overall, both studies noticed consistent concerns regarding the technical limitations and physiological side effects of VR/XR technologies. However, while Mergen's data suggest that these concerns may vary depending on user experience levels, the present findings indicate a more uniform perception across demographic and experiential groups.

6.1.7 Patient Interactions in VR/XR

Both the current study and Mergen's results indicate a cautious optimism toward the potential of VR/XR to support patient interactions in medical education, with higher confidence in basic examination tasks than in more complex interpersonal scenarios. In Mergen's cohort, 87.3% and 74.6% of participants considered visual and clinical examinations feasible, respectively, compared to 78.76% and 70.80% in the current study. Communication with virtual patients, however, received more reserved support: about two-thirds of Mergen's participants were open to interacting with virtual agents (66.3%), whereas only 34.51% of participants in the current sample affirmed imagining communication with XR patients, with a notably large proportion remaining undecided or disagreeing.

Regarding teamwork in XR environments, 62.3% of Mergen's students expressed positive attitudes, slightly lower than the 63.72% agreement observed in the present study. Similarly, holistic virtual patient simulations were endorsed by 24.6% fully convinced and 47.6% "Rather Yes" respondents in Mergen's data, while the current study found 63.72% agreement on the potential for holistic virtual simulations.

Statistical analyses in the current study revealed no significant associations between attitudes toward these patient interaction items and participants' age, XR familiarity, XR experience, or origin of experience, consistent with the relatively uniform perceptions in Mergen's sample. However, gender was significantly associated with teamwork attitudes, with males more likely to select "Definitely Yes" and females favoring "Rather Yes". Additionally, students' choice of instructional format had a significant impact on their responses, as those favoring practical classes were more likely to strongly agree with several statements, whereas students who preferred seminar or theoretical formats generally showed greater uncertainty or more moderate levels of agreement. These subtle differences were not reported in Mergen's report.

In sum, both datasets indicate that students generally support the use of VR/XR for patient examination tasks. However, more complex interactions like communication with virtual patients and teamwork receive more cautious responses. Some differences appear in levels of agreement and uncertainty, with demographic factors such as gender and class format preferences influencing perceptions.

6.1.8 Ideas for VR/XR-Scenarios

Free-text responses were provided by 104 students (41.3%) in Mergen's cohort and 32 participants (12.03%) in the present study, with suggestions aligning on several core areas for XR application in medical education. Surgical training was prominently emphasized in both datasets, with 43.3% of Mergen's respondents highlighting VR for surgical skill acquisition, and participants in this study frequently suggesting simulated operating room environments, surgical procedures, and realistic clinical settings as primary uses. Emergency medicine scenarios were also commonly mentioned, focusing on rapid decision-making in high-pressure situations.

Both groups recognized the value of XR for developing soft skills and psychological competencies; Mergen's cohort frequently suggested practicing delivery of bad news and managing emotional challenges, while this study's participants noted clinical consultation simulations and identified limitations of XR in replicating authentic patient communication and empathy.

Additional suggestions included clinical training beyond surgery and emergencies, such as internal medicine and routine clinical examinations in Mergen's data, and procedural practices like punctures and blood gas analysis in the current study. Preclinical education was notably supported, with anatomy receiving particular attention for its potential in 3D visualization of complex structures such as organs, vessels, nerves, and bones. Furthermore, participants in the present survey extended XR applications to biochemistry, pharmacology, and physiology, appreciating XR's capability to illustrate dynamic or abstract physiological and molecular processes.

In summary, both cohorts emphasize surgical and emergency training as key areas for XR development, with growing interest in soft skills, clinical procedures, and preclinical subjects.

6.2 Findings' Interpretation and Educational Relevance

The demographic profile of the study's participants offered a well-rounded representation of undergraduate medical students across age groups and academic years. Most were younger (aged 18–25) and female, with nearly 80% identifying as women, reflecting current enrollment trends in medical education [102]. In terms of academic standing, the concentration of participants in earlier years, particularly the second year, suggests that the insights gathered primarily reflect preclinical perspectives. This is relevant, as limited clinical exposure may shape their views on XR. At the same time, the smaller representation of senior students means findings may be less reflective of advanced clinical experience. Nevertheless, the overall diversity supports relevance across different student cohorts.

Awareness of XR terminology among students was low, indicating that these technologies are not widely recognized as a unified concept. This likely reflects a broader gap in exposure or education, which may limit students' readiness to engage with XR tools during training or future clinical work. Gender differences in XR familiarity mirrored broader societal patterns in technology engagement, emphasizing the need for equitable access and encouragement for all students. Students were also more familiar with VR and AR than with MR, reflecting general public exposure patterns. Many struggled to differentiate XR modalities, indicating a lack of conceptual clarity that could impair their ability to evaluate or select appropriate technologies for learning. Still regarding XR knowledge and experience, gaming emerged as the most common context for prior XR exposure, suggesting that student engagement with these tools is largely informal and recreational. This presents an opportunity to integrate XR more systematically into medical curricula, enabling more meaningful and skill-building experiences. The observed link between XR use, familiarity, and ability to distinguish modalities highlights the importance of hands-on exposure in developing technological literacy and confidence, putting into view clear opportunities to strengthen XR-related education in medical programs. By improving awareness,

providing accessible hands-on learning, and clarifying distinctions among XR types and their applications, institutions can better prepare students to use these technologies effectively.

Students' views on XR's role in medical education revealed openness to integrating such tools, even with limited prior exposure. There was strong agreement on XR's potential value, suggesting that perceptions of usefulness are driven more by future expectations than by direct experience. Nevertheless, students expressed a preference for XR integration in disciplines requiring spatial awareness, visualization, or procedural repetition. Clinical fields such as surgery, radiology, and emergency medicine were consistently mentioned, showing alignment between XR's capabilities and the demands of these subjects. In preclinical education, anatomy stood out as a natural fit, emphasizing XR's value in supporting structural understanding where physical resources may be limited. These preferences varied by age and year of study, where advanced students tended to favor XR in real-world clinical applications, and earlier-year students leaned toward foundational subjects; tendencies suggest that expectations for XR evolve with academic progression, from theoretical reinforcement to practical enhancement. Format preferences mattered as well, since students favored practical classes and evaluations for XR integration, reinforcing its value as an experiential tool. Even those more skeptical of XR favored its use in structured settings such as seminars, suggesting that reluctance may stem more from pedagogical concerns than outright rejection. Overall, students expressed specific, pedagogically oriented preferences for XR use. Their responses reflected an intuitive understanding of where XR adds value, particularly in bridging abstract knowledge with clinical application. These insights can guide educators and institutions in designing XR-enhanced curricula that meet learners' needs and expectations.

Students' perceptions of XR's advantages align with general pedagogical goals in medical education. There was a clear preference for immersive, simulation-based experiences that support knowledge acquisition and clinical competence. While competence improvement and interactive engagement were largely recognized, less emphasis was placed on features like rare condition depiction or scenario repeatability. This may reflect limited awareness or curricular exposure to these specific applications. Despite this, students in intermediate years were more likely to value XR's ability to represent rare diseases, likely due to increasing clinical awareness. Those who could distinguish between XR modalities perceived more benefits related to simulation range and skill development, suggesting that conceptual familiarity enhances perceived value. Conventionally, positive perceptions of XR integration correlated with recognition of its educational benefits, particularly in clinical reasoning and simulation. This implies that institutional support and visible use influence students' confidence in XR as a legitimate educational tool. On the other side, concerns about XR were consistent across groups, focusing on technical unreliability and the need for technological proficiency. Younger students were somewhat more likely to report concerns about technical malfunctions, possibly reflecting varying levels of digital confidence or sensitivity to usability issues. In general, while students broadly support XR integration, their perceptions are shaped by educational stage, technological familiarity, and exposure. These insights underscore the importance of aligning XR implementation with students' evolving needs and expectations to maximize impact and acceptance.

Most students viewed XR as a valuable educational tool and showed strong willingness to engage with XR-based learning. This enthusiasm may reflect awareness of XR's potential to enhance learning beyond traditional methods, in line with growing literature on immersive technologies in clinical training. Confidence was highest in XR's capacity to support visual and clinical examination of virtual patients; however, students were more cautious about applications involving communication with XR patients or teamwork simulations. This may reflect current technological limitations, limited exposure to advanced XR scenarios, or doubts about XR's ability to replicate complex interpersonal interactions. These patterns suggest XR development and integration should focus on areas where students already perceive clear benefits while addressing limitations in fidelity for more complex tasks. The moderate support for XR in teamwork training highlights an opportunity for further innovation in interprofessional and collaborative education. Furthermore, XR perceptions were influenced by gender and academic year. Female students were slightly more optimistic about XR's value, possibly reflecting differing learning preferences or attitudes toward technology. Early-year students showed more divided views, perhaps due to a combination of openness and limited clinical experience, while senior students were more cautious, likely due to increased clinical exposure and critical assessment of tools. When it came to classes format, students inclined toward practical, hands-on learning were more receptive to XR, while those favoring theoretical or seminar-based instruction were more reserved. This reinforces the importance of aligning XR implementation with learning styles and pedagogical approaches that emphasize active engagement. Generally, students' expectations for XR's future in medical education were optimistic. This outlook was not significantly influenced by demographics but was closely linked to perceptions of successful integration and preferred class formats. This suggests that positive experiences shape future expectations and acceptance. In summary, medical students are ready and willing to embrace XR, especially for enhancing clinical examination and practical skills. However, successful integration will require addressing concerns about more complex applications, such as communication and teamwork. Tailoring implementation to student preferences and improving technology's capacity to replicate interpersonal scenarios will be crucial to expanding acceptance and maximizing outcomes.

Finally for XR application ideas, students prioritized scenarios that emphasize hands-on, practical skill acquisition, especially in surgical and emergency medicine contexts. This reflects recognition of XR's ability to simulate high-stakes environments where repeatable practice is essential, and it also suggests XR is valued for filling experiential gaps in traditional education. Moreover, the prominence of these scenarios shows that students view XR as a meaningful tool for building clinical readiness, not just as novel technology. At the same time, interest in routine clinical tasks, such as patient consultations and basic procedures, demonstrates that students expect XR to support foundational skills as well. In preclinical education, students emphasized XR's ability to visualize anatomy and complex biological processes. This shows awareness of XR's cognitive value in translating abstract content into tangible experiences, aiding retention and comprehension. Yet, concerns about XR's limitations in replicating authentic patient interaction highlight a key pedagogical boundary. Students appear aware that while XR can simulate many clinical as-

pects, it may not yet capture the subtleties of empathy and communication. This suggests the need for hybrid approaches that combine XR with real patient encounters. Overall, students offered a down-to-earth and critical view of XR. They recognize its strengths in enabling safe, repeatable, and immersive practice, especially for technical and cognitive skills, while remaining mindful of its current limitations in interpersonal training. These insights can help educators and developers design XR tools that support both practical and relational learning goals.

In conclusion, XR technologies show strong potential, particularly in areas requiring spatial reasoning, procedural practice, and immersive simulation. However, limited familiarity and conceptual ambiguity among students indicate the need for early, structured exposure and foundational XR literacy within the curriculum. As students advance academically, their expectations evolve from theoretical reinforcement to clinical enhancement, supporting a phased approach to XR integration that aligns with educational progression. Strong preferences for hands-on formats and recurring concerns about XR's limitations in replicating interpersonal interactions suggest that XR should be implemented to complement, not replace real-world experiences. Educators and institutions should focus on applications where XR offers the greatest pedagogical value while investing in improvements that address its current shortcomings.

Chapter 7

Conclusion and Future Work

This chapter summarizes the key findings of the study and reflects on their significance for integrating XR in medical education (Section 7.1). It also highlights important considerations and potential directions for further exploration in this evolving field in Section 7.2.

7.1 Conclusion

This study investigated how medical students perceive the integration of XR technologies, comprising AR, MR, and VR, within medical education. In light of the growing interest in immersive technologies for training healthcare professionals, this dissertation aimed to explore not only students' awareness and attitudes but also the challenges and opportunities that may shape XR's educational impact. Through a targeted survey conducted at ICBAS, the study gathered insights into students' conceptual understanding, practical experiences, and expectations regarding XR. With these, the goal was to assess medical students' perceptions of XR technologies in education, evaluate their perceived usefulness, identify adoption barriers, and generate insights to guide future integration efforts.

Medical students demonstrated considerable enthusiasm for integrating XR technologies, recognizing their potential to enhance learning especially in areas requiring spatial awareness, visualization, and repetitive procedural practice, such as anatomy, surgery, and emergency medicine. However, the study revealed significant gaps in students' conceptual understanding and familiarity with XR modalities, with many struggling to differentiate between AR, MR, and VR. This highlights the need for foundational XR literacy to be formally incorporated into medical curricula to ensure students are well-prepared to engage with these tools effectively. While students valued XR's capacity for immersive and simulation-based learning, concerns were raised regarding the current technological limitations, particularly in replicating patient interactions and teamwork scenarios. These concerns suggest that XR should complement, rather than replace, real-world clinical experiences to foster comprehensive skill development. Additionally, variations in perception across academic years suggest that XR implementation must be adaptive, addressing the

evolving needs of learners, from reinforcing theoretical knowledge in preclinical years to supporting practical clinical skills in later stages. Overall, students favored hands-on, experiential learning formats for XR integration, emphasizing the importance of accessible, reliable technology coupled with ongoing support to build confidence and maximize educational benefit.

Informed by these findings, the study advises a strategic and phased approach to integrating XR into medical education. Initial efforts should focus on embedding basic XR literacy early in the curriculum, ensuring students gain conceptual clarity and confidence in using these tools. Integration should prioritize disciplines and learning activities where XR's immersive capabilities offer clear educational advantages, such as anatomy visualization and procedural simulations in surgery and emergency medicine. It is equally crucial to address technical challenges proactively and provide robust institutional support to minimize barriers related to usability and reliability. Tailoring XR applications to align with students' academic progression and preferred hands-on learning modalities will optimize engagement and effectiveness. By adopting such an approach, medical schools can use XR to enrich traditional teaching methods, bridge experiential gaps, and ultimately prepare students for a technology-augmented clinical environment with greater competence and confidence.

7.2 Future Work

Building on the insights from this study, future research should adopt a more comprehensive and multi-perspective approach to XR integration in medical education.

One promising direction is to extend investigations beyond students to include medical educators and clinical instructors. Understanding teachers' attitudes, preparedness, and perceived challenges regarding XR could reveal critical factors influencing successful implementation and help tailor training programs that address faculty needs. This dual perspective would foster alignment between learner expectations and teaching practices, creating a more cohesive XR-enhanced learning environment. Furthermore, practical experimental studies are needed to evaluate the real-world effectiveness of XR tools in medical curricula. Pilot programs implementing specific XR technologies, such as VR anatomy modules or AR-guided procedural simulations, can provide valuable data on student engagement, learning outcomes, and usability issues. These trials should employ mixed methods, combining quantitative performance measures with qualitative feedback, to capture a holistic picture of XR's educational impact. Special attention should be given to investigating how XR integration affects development of both technical skills and softer competencies like communication and teamwork, areas where this study identified current limitations and skepticism among students.

In summary, by bridging the gap between educators and learners, and systematically testing XR applications in real-world settings, future research can not only enhance the effectiveness of these technologies but also ensure their sustainable adoption. Ultimately, such efforts will contribute to more immersive, interactive, and impactful learning experiences that better prepare medical professionals for the complexities of clinical practice.

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Appendix A

State of The Art Summary Table

Table A.1: Table showcasing the main information from the articles included in Chapter 3.

#	Article Identification	Year of Publication	Journal	Technology	Application	Educational Indicators	Advantages	Disadvantages	Future Work
1	Pieterse [50]	2023	Virtual Reality	360° video-based Virtual Reality	Preparing medical students for clerkships through immersive exploration of a hospital ward and observing professional behavior	Preparedness for clerkships; ability to observe and identify unprofessional behavior; engagement with interactive VR	Realistic and immersive; innovative learning tool; enhances focus and insight; helps students feel more prepared for hospital environments	Physical discomfort; disconnection between physical and virtual environments; technological limitations	Conduct studies to test effectiveness compared to traditional methods; evaluate long-term use after novelty fades; explore improvements in hardware resolution and navigation mechanisms
2	Ryan [51]	2023	International Journal of Gynecology and Obstetrics	Virtual Reality	Teaching embryology, specifically fetal development	Knowledge improvement; satisfaction; self-confidence in learning	Enhancing understanding of complex topics; improving satisfaction and confidence in learning; promoting long-term retention	Cybersickness; symptoms like dizziness, and disorientation	Studies with larger cohorts; advancements in VR technology to reduce cybersickness
3	d'Aiello [52]	2023	Journal of Medical Systems	Microsoft HoloLens 2.0, ARTICOR® software, Mixed Reality	Teaching of congenital heart disease anatomy and transcatheter treatment	Proficiency in disease anatomy; understanding of procedural treatment and complications	Better anatomical understanding; increased student engagement; improved learning efficiency; immersive experience; potential for remote learning	Difficulty in initial use of devices; potential distractions; need for accurate simulations	Pre-class assessment of student proficiency; inclusion of more spatio-visual items in questionnaires; qualitative study for deeper exploration of student perceptions; more comprehensive studies
4	Gao [53]	2023	BMC Medical Education	3D Virtual Reality Simulation	Teaching Human Parasitology	Knowledge acquisition; delayed retention; subjective task values	Improved learning; better knowledge retention; increased student motivation and interest	Technical issues with VR equipment; potentially uncomfortable for prolonged use; expensive; requires specialized hardware	Future studies with true experimental design; research on how VR impacts motivation and autonomy; studies on VR's impact on other medical courses
5	Moro [54]	2023	Medical Science Educator	Augmented Reality	Medical pathology education, specifically lung pathology	Medical student perceptions, impact on learning, preference for AR vs. physical specimens	Interactive learning and multiple view angles; Accessible for self-study; Cost-effective; Enhances spatial understanding; Potential for reducing cadaver shortages	Perceived as unrealistic and oversimplified; Lack of tactile learning; Limited clinical preparedness; Limited variety in models	Further studies on performance outcomes; Longitudinal perception studies; Investigate varied AR content for pathology

#	Article Identification	Year of Publication	Journal	Technology	Application	Educational Indicators	Advantages	Disadvantages	Future Work
6	Malik [55]	2023	Laryngoscope	Microsoft HoloLens2™, Mixed Reality	Remote teaching for medical students in ear, nose, and throat education	student engagement, performance, and feedback	Provides immersive 3D visualization for better conceptual understanding; enhances a sense of presence with real-time auditory and visual information; promotes interactive and engaging learning	Technical issues include disappearing holograms, loss of calibration, and degraded streaming quality; causes motion sickness in some users; high cost of equipment and setup	Further trials with randomly selected cohorts to reduce volunteer bias; optimization of development and pedagogy for immersive technologies in medical education
7	Michalski [56]	2023	Translational Research in Anatomy	Mixed Reality	Used to study heart anatomy asynchronously following synchronous learning	Cognitive load assessed using the Cognitive Load Component questionnaire	Reduced cognitive load compared to synchronous learning; greater focus during the MR learning activity	limited generalizability due to specific MR design	Larger sample size needed in future studies; explore MR for different anatomical topics
8	Hutchcraft [57]	2023	Multimodal Technologies and Interaction	RTB software (smartphone/tablet applications and Immersive Virtual Reality platforms)	Teaching obstetric anatomy and physiology to medical students	Mental rotation test, in-software quiz performance, student feedback (survey and focus group), technology use patterns	Portable, convenient for study, good quiz performance, potential for patient education, improved understanding of obstetric pathology	Artwork quality not meeting medical standards, small smartphone screen, IVR setup inconvenience, reluctance to use IVR	Improve RTB software features, evaluate further integration into curricula, explore use in patient education, optimize IVR content
9	da Cruz Torquato [58]	2023	Medical Science Educator	Virtual Reality	Anatomy learning	Short-term retention; Medium-term retention; Long-term retention; Student satisfaction	Increased engagement; 3D visualization of anatomical structures; positive student feedback on VR's usefulness as a supplementary method	No significant improvement in knowledge retention; high cost; time-consuming; students did not find VR improved academic performance	Larger studies with larger sample sizes; more robust research on the impact of VR in medical education; exploration of AR and VR integration
10	Stackhouse [59]	2023	Advances in Medical Education and Practice	Microsoft HoloLens 2, Mixed Reality	Teaching clinical medicine	Knowledge attainment; student engagement; student enjoyment	Scalable for large groups; feasible for remote teaching; effective for knowledge delivery	High resource demands; requires technical setup; limited interactivity compared to other methods	Explore clinical and professional skills assessment; test MR with smaller groups; investigate reasons for varying student engagement
11	Kim [60]	2023	Cureus	Virtual Reality	Teaching pharmacology	Knowledge improvement; Self-rated confidence; Satisfaction; Ease of use; Perceived usefulness; Quality of visuals; Comfort level	Immersive 3D visualization; Self-paced learning; Increased engagement and confidence	Cybersickness; Discomfort from wearing the device	Long-term effectiveness; Integration into medical curricula; Larger-scale studies
12	Liao [61]	2024	Anatomical Sciences Education	VR anatomy instruction video using 3D Organon software	Anatomy education for large classes with limited VR hardware and resources	Student engagement in peer discussions; student perception of learning enhancement for gross anatomy; incidence and impact of visually induced motion sickness (VIMS) on learning	Effective for large class sizes with limited equipment; facilitates peer discussions; supports comprehension of 3D anatomical structures; helps streamline learning and reduces waiting times for VR equipment	High incidence of VIMS, especially in female students; discomfort may hinder concentration and willingness to use VR	Expand VR instruction to additional anatomy systems; assess asynchronous online learning platforms; examine screen size impact on VIMS; consider integrating VR with other multimedia tools
13	He [62]	2024	BMC Medical Education	Virtual Reality + Case-Based Learning	Medical education, particularly in anatomy and rehabilitation therapy	Test scores (knowledge retention, skill development); student satisfaction; teacher-student interaction	Enhanced knowledge retention; improved student engagement; interactive and immersive learning experience; higher satisfaction in VR-enhanced groups	Limited applicability in rehabilitation therapy; VR technology still evolving	Expand sample size; explore VR technology in other medical fields; conduct longitudinal studies; assess long-term knowledge retention and clinical skills development
14	Rudolph-Solero [63]	2024	Journal of the American College of Radiology	Virtual Reality, Second Life Metaverse	Radiology learning	High test scores; positive feedback; improved teamwork; moderate to high cognitive load for reading content and tests; high perceived usefulness for learning radiology	Feasible and reproducible across universities; motivates students through team competition; encourages social interaction during COVID-19; reinforces radiology knowledge; fun and engaging learning experience	Technical issues (poor internet connection, insufficient computing capacity); difficulty navigating Second Life and managing avatars	Increase social interaction between participants from different universities; modify rules to encourage collaboration and strategies; adapt game for interhospital competition with radiology residents; continue refining technology to avoid technical problems
15	Truckenmueller [64]	2024	World Neurosurgery	Augmented 360° 3D Virtual Reality	Early medical student education in neurosurgery	Increased student interest; enhanced conceptual knowledge of procedures; improved understanding of operating room workflow	Engages students early; enhances understanding of complex concepts; provides interactive learning; fosters positive perceptions of neurosurgery; allows for self-directed learning	High production costs; labor-intensive; challenges with widespread implementation	Customization of content for different experience levels; implementation of interactive element; creation of online VR library for global access; reducing costs and simplifying technology

#	Article Identification	Year of Publication	Journal	Technology	Application	Educational Indicators	Advantages	Disadvantages	Future Work
16	Neri [65]	2024	Anatomical Sciences Education	Augmented Reality	Human anatomy education	High quiz scores for theoretical and practical knowledge; student enjoyment; interest in future use of AR	AR increases engagement, motivation, and interest; effective for both theoretical and practical learning; useful for medical practice	Technical issues; limited differentiation in prior AR experience; small sample size for interviews	Further study on cognitive processes and cognitive load; assess how AR can be more effective in human anatomy learning
17	Wach [66]	2024	Neurosurgical Focus	Mixed Reality, Microsoft HoloLens	Neurosurgical education, specifically neuroanatomy and neurosurgical techniques	Interest in MR courses; Support for MR integration in curriculum; Perceived improvement in neuroanatomy understanding; Preferred early integration in curriculum; Preference for experienced instructors	Enhanced understanding of neuroanatomy and surgical techniques; Allows early exposure to 3D learning and surgical concepts; Interactive, group-based teaching using MR technology	High cost of MR equipment; need for technical infrastructure; accessibility challenges	Further evaluation of MR's impact on understanding neuroanatomy and surgical approaches; Development of MR curricula to enhance recruitment in neurosurgery; Future studies focusing on separate groups of students with and without MR experience.
18	Abundez Toledo [67]	2024	Frontiers in Virtual Reality	Virtual Reality	Anatomy education	Student comfort with VR technology; perceived effectiveness in learning anatomy better than lectures; perceived retention of information after VR training; opinions on VR as a tool to supplement anatomy labs; opinions on VR replacing traditional methods	Easy to navigate; comfortable experience for most participants; helps with information retention; flexibility in learning environment; can be used for other subjects beyond anatomy; access to VR would be beneficial for medical schools	Some discomfort with prolonged headset use; learning curve for first-time users; financial barriers if headsets are not provided by schools; cannot fully replace in-person cadaver labs	Exploring long-term effectiveness of VR in education; further integration of VR in medical curricula; investigation into the impact of VR on clinical skills and knowledge retention; comparison with other tools like 3D anatomy apps
19	Würstle [68]	2024	Journal of medical education and curricular development	Virtual Reality	Educational VR course on pancreatic cancer using EVENT software	Test score improvement, Engagement, Usability, Self-efficacy increase	No programming skills required to develop lessons; significant learning improvement; high usability and student satisfaction; good for students without prior VR experience	Cyber-sickness reported by 15.4% of students; stress caused by performance pressure in immersive environments; need for sufficient physical space to avoid movement constraints	Comparative studies with 2D e-learning and interactive seminars to evaluate immersion benefits; analysis of long-term retention of acquired knowledge
20	Deuchler [69]	2023	Ophthalmology and Therapy	Eyeslit Lamp Simulator, Virtual Reality	Training for slit lamp examination	OSCE scores; post-assessment survey; knowledge gain; skill acquisition	Improved practical skills; increased knowledge; better ability to recognize pathologies; self-guided learning; stress-free training	High cost; lack of tactile feedback compared to real patient exams; limited to virtual scenarios	Comparing the efficiency of simulator vs. traditional training with equal time; validating the slit lamp simulator; studying long-term effects; evaluating additional tools like gonioscopy and funduscopy
21	Mergen [70]	2023	Education Sciences	Virtual Reality	Medical Education	Survey responses from 252 medical students, including questions on experience, expectations, and perceived advantages/disadvantages	Enhances procedural skills training; Allows repeated practice in a safe environment; Interactive learning; Improves medical competencies and clinical reasoning; Provides simulation of rare diseases	Technical requirements/competencies; Technical susceptibility to errors; "Cybersickness"; Unrealistic scenarios	More studies on VR use in medical curricula; Development of VR for soft skills training and non-technical skills; Advancing AI to improve realistic communication in virtual patients
22	Mahling [71]	2023	Journal of Medical Internet Research	Virtual Reality	Emergency Medicine Training	Questionnaire results (student perceptions, physical symptoms, confidence, empathy)	Useful for conveying complex issues; Supplement to face-to-face training; Ability to repeat scenarios; Allows for failure and feedback	Low confidence in medical content; Low empathy with virtual patient; Physical symptoms like dizziness; Gender differences in perceptions	Investigate impact on real-world patient outcomes; Improve VR course design to overcome technical limitations; Explore the role of empathy in VR scenarios
23	Knudsen [72]	2023	Journal of Medical Internet Research	360-degree VR videos with integrated multiple-choice questions (MCQs)	Assessing emergency medicine skills	Igroup Presence Questionnaire; NASA-TLX; 360MedQuest score; Cronbach alpha for reliability	High immersion; Standardized scoring; Eliminates rater bias; Reproducible assessments; Can be used under social distancing conditions	Limited to MCQs with single answers; Risk of type I error from multiple tests; Less transferable to real-life decisions	Investigate use in postgraduate skills assessment; Explore as an education tool
24	Jensen [73]	2023	Journal of Clinical Imaging Science	Virtual Reality	Training students in correct positioning of wrist radiographs	Self-perceived clinical readiness before and after VR training; Usability of the VR system; Feedback on realism and educational value of the VR system	No radiation exposure; Immediate feedback on positioning; Positive feedback on system realism; Ability to practice without patient involvement	No tactile feedback for palpating anatomical landmarks; Lack of patient interaction; Results not statistically significant for self-perceived clinical readiness improvement	Larger studies with more participants; Investigating the clinical effect of VR training; Gathering validity evidence for VR-based simulation tests in radiography

#	Article Identification	Year of Publication	Journal	Technology	Application	Educational Indicators	Advantages	Disadvantages	Future Work
25	Silvero Isidre [74]	2023	Medicina (Lithuania)	Mixed Reality	Neurosurgical training; 3D model interaction; Surgical planning	Satisfaction scores; Usefulness and implementation feedback; General assessment of MR technology	Immersive; Interactive; Enjoyable; Improves satisfaction; Facilitates complex training	Cannot fully replace physical models; Limited haptic feedback	Integrate MR with cadaveric/physical models; Enhance retention and practical training
26	Jacobs [75]	2023	Journal of Visual Communication in Medicine	Virtual Reality	Sepsis identification and management simulation for healthcare professionals	Immersion, intrinsic motivation, cognitive load, system usability, debrief	High immersion, high intrinsic motivation, good system usability, psychological safety, repeatable practice	Connectivity issues (Wi-Fi), cognitive load challenges, technology interface issues for novice learners	Comparison with traditional manikin simulation, exploration of performance outcomes, addressing adoption barriers
27	Cheung [76]	2023	International Journal of Gynecology and Obstetrics	Virtual Reality	Training medical students to acquire vaginal examination skills	Clarity of instructions; ease of learning; recall of task details; ability of VR to facilitate learning and interaction; motivation to learn	Immersive, interactive training; safe and controllable conditions; repeatable practice; no patient involvement; self-paced learning; no resource waste	High cost; requires specific equipment (headset, motion controller); limited availability of VR models; lacks detailed feedback on technique	Larger studies; comparison with traditional methods; expanding VR use for other procedures and clinical scenarios
28	Gan [77]	2023	BMC Medical Education	Virtual Reality	Tendon suturing training	Clinical practice scores; OSCE scores; survey responses	Immediate feedback; task decomposition; enhanced learning experience	High costs; lack of resources for continuous use; limited to certain procedures	Integration of VR into broader clinical education; reducing costs; expanding multidisciplinary VR use
29	Gsaxner [78]	2023	Medical Image Analysis	HoloLens (Augmented Reality Head-Mounted Display)	Medical imaging; Surgical guidance; Educational training; Patient monitoring	Engagement; Motivation; Learning effectiveness	Small form factor; Low cost; Effective for less precise procedures; Enhances student engagement and motivation	Limited precision and accuracy for image-guided surgeries; Line-of-sight constraints; Depth perception issues; Registration errors	Improving precision and reliability for image-guided surgeries; Exploring marker-less registration strategies; Addressing eye calibration and perceptual issues; Enhanced collaboration between researchers, clinicians, and patients
30	Rickenbacher-Frey [79]	2023	GMS journal for medical education	Virtual Reality	Training to manage acutely ill patients with dyspnoea	System Usability Scale; After-Scenario Questionnaire; User Satisfaction Evaluation Questionnaire; Training Evaluation Inventory; Confidence levels; Mental workload	High immersion and presence; safe practice; minimal simulator sickness; good usability and user satisfaction; enhances learner engagement; complements physical simulations	Limited virtual reality technology; cognitive overload in multiplayer settings; requires significant collaboration; not yet personalized for learner levels	Further development of virtual reality hardware; personalization of simulations; multiplayer settings; expansion to higher levels of training evaluation
31	Guerrini [80]	2024	Brain Sciences	Augmented Reality	Surgical training in neurosurgery	Increased interest in surgical specialties; improved confidence with surgical instruments	Enhanced student motivation and interest in neurosurgery; hands-on experience in a low-risk environment	Technical complexity; Applicability challenges; High costs; Limited real-life scenario adherence	Long-term studies to evaluate sustained interest and effectiveness
32	Deuchler [81]	2024	Ophthalmology and Therapy	Slit Lamp Simulator, Virtual Reality	Fundus Biomicroscopy Training	Improved performance scores in OSCE; better self-assessment of skills	Enhanced learning experience; ability to practice without patient burden	Simulator may not fully replicate real-life patient interactions; Limited ability to simulate patient-specific variables	Need for longer training periods to improve diagnostic skills
33	Singh [82]	2024	Virtual Reality	Virtual Reality	Knee arthrocentesis training	OSCE scores; student confidence; understanding of procedure	Improved scores; positive student feedback	Technical difficulties with VR headset; Issues for students wearing glasses; Glitches affecting the immersive experience	Enhance immersion with walking capabilities; explore haptic feedback technology
34	Mergen [83]	2024	Education and Information Technologies	Valve Index VR-Kits, Virtual Reality	Skin cancer screening training	Increased self-competence; perceived immersion; usability ratings; enjoyment	Positive feedback on VR integration; practical experience in a simulated environment; enhanced learning through observation	Cybersickness issues during VR use; VR system can cause discomfort, such as eye strain; Technical problems with VR equipment, such as malfunctioning or inadequate tracking of user movements; Requires a high degree of technical support during use	Follow-up studies to validate findings; explore long-term retention of skills; clinical transferability of knowledge
35	Alieldin [84]	2024	Virtual Reality	Immersive Virtual Reality	Empathy training for first-year medical students	Changes in empathy scores; participant self-reports	Enhances empathy; provides immersive experience; allows perspective-taking; effective for understanding patient experiences	Cost of implementation; limited interactivity	Further research with larger samples; comparison studies with control groups; explore additional applications of IVR in medical education

#	Article Identification	Year of Publication	Journal	Technology	Application	Educational Indicators	Advantages	Disadvantages	Future Work
36	Johnston [85]	2024	BMC Medical Education	Microsoft HoloLens 2	Medical student education in clinical settings, remote learning during clinical encounters	Usability; Feasibility; Learning Engagement; Learner Satisfaction; Clinical Integration	High usability for teaching clinical skills; Provides remote access to bedside teaching; Positive student and patient feedback; Allows visualization of 3D anatomy; Allows consistent clinical teaching delivery	Technical issues with Wi-Fi connectivity; HL2 has a training curve for clinician; Not suitable for all types of patients	Explore the scalability of MR-based teaching resources; Develop a library of MR teaching sessions for self-paced learning; Investigate further integration of MR for specific applications like surgery and regional anesthesia; Assess long-term effects of MR on clinical competencies; Expand research to include more diverse patient populations and medical specialties
37	Junga [86]	2024	Journal of the European Academy of Dermatology and Venereology	Virtual Reality, Valve Index VR Headset, Unity Game Engine, Character Creator 3, motion tracking, diffusion models	VR-based skin cancer screening simulation for medical students, focusing on diagnosis and examination of skin lesions	Subjective competence in performing skin cancer screening; usability; cognitive load; realism; and immersion of VR simulation	Provides a standardized learning experience for all students; Allows for repeated practice; Can simulate difficult-to-replicate situations in dermatology; Positive feedback from students, including perceived usefulness and fun; No patient availability issues; Offers a low-risk environment for learning	High cost of VR hardware and software; Technical limitations; Uncertainty in dermatoscopic images due to technical constraints; Some students reported mild cybersickness symptoms	Improve VR scenario with enhanced dermatoscopic images; Allow avatar communication via voice; Extend examination to mucosal membranes; Reduce VR hardware/software costs over time; Develop additional VR scenarios for dermatological education
38	Nuutinen [87]	2024	Simulation and Gaming	Fully immersive HMD VR-simulation vs. video lecture	Training for abscess incision in undergraduate medical students	Knowledge; self-confidence, usability; learning value	VR allows for procedure repetition, enhances active learning, offers a patient-safe environment; video is convenient and familiar	VR is less technically usable than video; some students experience nausea; lacks tactile feedback; VR requires technical support	Develop validated survey tool; consider prior knowledge level; further explore VR impact on technical skills
39	Liang [88]	2024	BMC Medical Education	Virtual simulation platforms	Medical education practical training	Learning satisfaction (dimensions: student, course, technical, embodied); Learning motivation; Task value; Social and spatial presence; Self-efficacy	Enhances engagement, allows immersive learning, offers realistic practice environments, supports personalization, fosters collaboration	Requires high-end hardware; potential technical issues; limited learning flexibility	Broader sampling to improve generalizability; Exploration of causal relationships; Emphasis on instructor roles; Development of universally applicable models for satisfaction factors in virtual simulation experiments
40	Walls [89]	2024	BMC Medicine	Virtual Reality, Desktop simulation	Medical education, Emergency simulation training (cardiac arrest, life-threatening asthma)	Heart rate (engagement); Time on task (focus/engagement via eye tracking); Subjective engagement and enjoyment (surveys)	VR is more engaging and enjoyable than standard desktop simulation; Cost-effective compared to traditional simulation suites; Scalable for larger groups; No need for physical space or facilitators for multiple students	VR headset and video quality issues (e.g., lower resolution compared to desktop); Potential for motion sickness (though not observed in this study); Technological barriers, including the need for proper hardware and software.	Compare VR simulation with in-person simulation using subjective measures and physiological data; Investigate long-term knowledge retention after VR training; Further studies on VR simulation in clinical settings with larger and more diverse groups
41	Malone [90]	2024	Annals of Medicine	Virtual Reality and High-Fidelity Simulation	Assessing EPA-10 skills (critical care patient management)	Student performance; Entrustment ratings; Feedback; Teaching effectiveness	Provides a low-cost, scalable platform for formative assessments; VR allows for deliberate practice; high-fidelity (HF) is more realistic and conducive to team learning; Positive feedback about instructor coaching/feedback during simulations	Technical issues with VR motion sickness, navigation challenges; VR students require more practice to acclimate; HF simulations may be more familiar and easier to use; VR platform requires students to handle all tasks no nurse confederate; VR has fewer immersive aspects compared to HF	More controlled studies comparing formative vs. summative assessments; Improve VR technology to reduce technical issues, such as motion sickness; Explore the cost-benefit of VR vs. HF simulations; Research on student acclimation to VR environments and its impact on performance

#	Article Identification	Year of Publication	Journal	Technology	Application	Educational Indicators	Advantages	Disadvantages	Future Work
42	Willis [91]	2024	Journal of the Intensive Care Society	Assisted Reality, AMA Xpert Eye assisted reality glasses	Teaching medical students intensive care medicine through live streaming from the Intensive Care Unit (ICU)	Strong learner satisfaction with session organization, objectives, and technology; Positive feedback on engagement and relevance of the session; Minor issues with feedback availability and impact on future practice	Enables remote learning in a safe, non-disruptive environment; Facilitates interaction with ICU equipment and real-world scenarios; Technology was well-received by students; Overcame COVID-19-related access restrictions	High cost of technology; Technical difficulties; Challenges integrating teaching with clinical duties of ICU staff	Potential for using augmented or virtual reality for more immersive learning; Exploring patient perceptions of the technology; Cost-effectiveness analysis for broader implementation; Training for new educators and integration into regular ICU education
43	Jensen [92]	2024	Radiography	Virtual reality simulation	Training radiographers in wrist radiograph acquisition and positioning in a VR environment	Accuracy in assessing radiographic positioning; trends between confidence and performance	Provides practice-oriented learning without patient involvement or radiation exposure; potential for feedback integration; environmentally friendly (reduces carbon footprint)	Lack of tactile interaction	Explore larger, homogeneous cohorts; evaluate VR feedback mechanisms' impact on learning and clinical practice; refine VR training tools to enhance engagement and skills
44	Clarke [93]	2024	BMJ Open Quality	Mixed Reality Headsets, Microsoft HoloLens	Emergency trauma simulation for junior medical trainees	Knowledge recall and retention; Improved preparedness to manage high-acuity trauma; Supervisor appraisals; Student feedback	Higher knowledge scores and better retention compared to traditional teaching; Ability to simulate complex, high-acuity trauma scenarios safely; Remote learning potential; Reduces cognitive load in some students	High cost of MR devices; Novelty might affect student engagement	Further research with randomized design; Study comparing MR simulation with high-fidelity simulation; Longer follow-up on knowledge retention; Investigating long-term sustainability of MR technologies in education
45	Pedram [94]	2024	Virtual Reality	Head-Mounted Display Virtual Reality	Medical Training (specifically Arterial Blood Gas Collection Collection)	Self-efficacy; Knowledge Test Scores; Active Learning, Cognitive Benefit; Reflective Thinking; Skill Acquisition; Simulation Sickness; Physical Strain and Stress	Improved practical skills performance; Better safety and hygiene adherence; Higher completion rate; Low levels of simulation sickness; High engagement; Presence and Fidelity	Preference for trainer presence; Limited to a single training scenario	More participants with diverse backgrounds; Different training scenario; Longitudinal study on training transfer; Investigate transfer to real-world clinical practice
46	Einloft [95]	2024	BMC Medical Education	Extended Reality , Virtual Reality	STEP-VR application for medical emergency simulations	Student acceptance; Ease of handling HMD; Content complexity; Immersion; Learning success; Seminar design; Simulation sickness	High engagement and immersion; Realistic emergency scenarios; High perceived educational value; Cost-effective compared to physical simulations; Minimal simulation sickness	Some students felt the simulation was not realistic enough; Minor gender differences in ease of use	Long-term effects on clinical practice and patient care; Scalability of VR programs; Integration of XR/VR into medical curricula
47	Birrenbach [96]	2024	BMC Medical Education	Virtual Reality	Trauma training simulation for ATLS preparation	Student confidence; Simulation effectiveness; Training feasibility; Simulation usability; Confidence in trauma care	Feasible; Improves confidence in trauma care; High user satisfaction; Good usability; Minimal simulator sickness	No improvement in objective knowledge and skills; One participant had severe motion sickness; Gender differences in VR acceptance	Long-term effects on trauma care performance; Further integration of VR into trauma training programs; Exploration of more challenging scenarios
48	Dunlop [97]	2024	Frontiers in Medicine	Virtual Reality	VR Learning Environment (VRLE) for teaching medical students about postpartum hemorrhage emergency management and postpartum balloon insertion	Improvement in knowledge of PPH management; increase in student confidence; student satisfaction with learning experience	Faster completion of postpartum balloon insertion task with VRLE; high student engagement and satisfaction with VRLE; VRLE offers a safe, repeatable environment for practicing hands-on skills	Some students experienced side effects such as eye strain, disorientation, blurred vision, and nausea; small sample size may limit generalizability; cost and maintenance of VR technology could be a barrier	Larger studies with more participants to further assess the effectiveness of VRLE in medical education; exploration of VRLE for teaching additional procedural skills in obstetrics and gynecology
49	Schöbel [98]	2024	Orthopädie	Immersive Virtual Reality (iVR), Oculus Quest 2 headsets, PrecisionOS platform	Surgical skills training in orthopedic surgery for medical students	Theoretical and procedural surgical knowledge; user satisfaction; procedural knowledge improvement	iVR improves procedural knowledge, enhances student understanding, cost-effective, positive student feedback, easy integration into curriculum	Occasional technical problems; lack of haptic feedback; motion sickness in some students; limited hardware access and infrastructure for large groups	Further integration of iVR in medical education; expanding software modules for additional procedures

#	Article Identification	Year of Publication	Journal	Technology	Application	Educational Indicators	Advantages	Disadvantages	Future Work
50	Meng [99]	2024	Frontiers in Medicine	Virtual simulation technology	Clinical microbiology examination for medical examination technology students	Experimental and theoretical test performance; student satisfaction; learning effectiveness	Improved student performance in practical skills and theoretical knowledge; enhanced clinical thinking; student engagement; high satisfaction with virtual simulation	Cannot fully replicate real experiments; Limited to theoretical scenarios; Need for real experiments to complement virtual simulations	Explore the role of specific influencing factors; continue teaching reforms across multiple classes to ensure result reliability
51	Stauffer [100]	2024	International Journal of Computer Assisted Radiology and Surgery	Augmented Reality, Cube Navigation System	Teaching radiologists the usage of the Cube Navigation System	Correctness of needle coordinates; Cube rotation; User experience	Reduction in cube rotation; Positive user experience; Immediate feedback provided during the training	Inability to replicate real-world clinical conditions	Evaluating training in a real-world clinical scenario; Comparing puncture accuracy between the two groups; Including practitioners in future studies; Increasing sample size in future studies
52	Lovett [101]	2024	Cureus	Augmented Reality, Microsoft HoloLens	AR-guided suture guidance application for practicing wound closure	Total number of stitches placed; Ratio of stitches bisecting the wound; Total wound closure time; Symmetry of stitch bite; Width of the stitch; Angle of stitches; Spacing between stitches	Improved suture technique and performance (fewer stitches, greater spacing between stitches); Supported independent practice; Complemented instructor-led training	Hologram instability affecting precise stitch guidance; Uncomfortable neck positioning with HoloLens; Limited feedback on stitch depth and efficiency of motion	Improve hologram stability; Address neck positioning issues; Expand application to more complex wound closure scenarios; Explore XR technologies for more immersive training

Appendix B

Survey

Inquérito a Estudantes: Realidade Estendida (XR) no Ensino Médico

O presente inquérito surge no âmbito da Dissertação de Mestrado em Engenharia Biomédica. Este é anónimo e tem como objetivo avaliar a experiência, as expectativas e as perspetivas dos estudantes de medicina sobre o uso da Realidade Estendida (XR), incluindo Realidade Aumentada (AR), Realidade Mista (MR) e Realidade Virtual (VR), no ensino médico. A participação neste inquérito é completamente voluntária, e os participantes têm a liberdade de se retirar a qualquer momento, sem qualquer repercussão. O questionário encontra-se implementado numa conta Microsoft abrangida pela licença subscreta pela Universidade do Porto. Ao longo do inquérito, não será solicitada informação que permita identificá-lo(a). Os dados recolhidos serão tratados de forma confidencial e utilizados apenas para o contexto académico.

Para qualquer esclarecimento adicional contactar:
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* Obrigatório

- ☐ – Escolha única
- ☐ – Escolha múltipla

A. Informação de Contexto

Nesta secção, é solicitada a recolha de informações básicas acerca dos participantes com o intuito de avaliar o nível de conhecimento atual sobre o tema em questão.

1. Qual é a sua idade? *

- ☐ 18 - 20 anos
- ☐ 21 - 25 anos
- ☐ 26 - 30 anos
- ☐ 31 - 35 anos
- ☐ >35 anos

2. Qual é o seu género? *

- ☐ Feminino
- ☐ Masculino
- ☐ Outro
- ☐ Prefiro não responder

3. Em que ano do ensino pré-graduado está a estudar? *

- ☐ 1º ano
- ☐ 2º ano
- ☐ 3º ano
- ☐ 4º ano
- ☐ 5º ano
- ☐ 6º ano

B. Percepção de Utilidade

Caso não esteja familiarizado com os conceitos de Realidade Estendida (XR), Realidade Aumentada (AR), Realidade Mista (MR) e Realidade Virtual (VR), aqui são apresentadas breves definições das mesmas. Assim, torna-se possível o preenchimento informado das próximas questões relacionadas com a utilização destas tecnologias.

- Realidade Estendida (XR): É um termo abrangente que inclui todas as tecnologias que combinam o mundo físico e o virtual, como a realidade aumentada (AR), a realidade mista (MR) e a realidade virtual (VR). Refere-se ao conjunto de experiências que expandem ou transformam a nossa percepção do mundo real através de meios digitais.
- Realidade Aumentada (AR): Tecnologia que sobrepõe elementos digitais (como imagens, sons ou informações) ao mundo real, geralmente através de dispositivos como smartphones ou óculos específicos. O utilizador vê o ambiente físico com gráficos ou informações digitais incorporadas.
- Realidade Virtual (VR): Tecnologia que cria um ambiente digital completamente imersivo, separando o utilizador do mundo real. Utiliza dispositivos como óculos de VR, que bloqueiam a visão do ambiente externo e colocam o utilizador num cenário virtual tridimensional.
- Realidade Mista (MR): Combina elementos de realidade virtual e aumentada, permitindo a interação em tempo real entre objetos virtuais e o mundo real. É possível, por exemplo, manipular objetos virtuais que "reagem" ao ambiente físico circundante.

4. Estava familiarizado com o conceito de Realidade Estendida (XR)? *

- ☐ Sim
☐ Não

5. Selecione todas as opções de que já ouviu falar entre Realidade Aumentada (AR), Realidade Mista (MR) e Realidade Virtual (VR): *

- | | |
|---|---|
| ☐ Realidade Aumentada (AR) | ☐ Realidade Virtual (VR) |
| ☐ Realidade Mista (MR) | ☐ Nenhuma |

6. Consegue distinguir entre Realidade Virtual (VR), Realidade Aumentada (AR) e Realidade Mista (MR)? *

☐ Sim

☐ Não

7. Já utilizou Realidade Estendida (XR) antes? *

☐ Sim

☐ Não

8. Se sim, em que área teve contacto com Realidade Estendida (XR)?

☐ Jogos

☐ Estudos/Profissão

☐ Outro: _____

9. Consegue imaginar uma integração útil da Realidade Estendida (XR) no ensino médico? *

☐ Sim

☐ Não

10. Em quais disciplinas clínicas imagina existir maior potencial para a utilização da Realidade Estendida (XR)? *

☐ Anestesiologia

☐ Cirurgia

☐ Dermatologia

☐ Farmacologia

☐ Ginecologia

☐ Infeciologia

☐ Medicina de Emergência

☐ Medicina Forense

☐ Medicina Geral

☐ Medicina Interna

☐ Medicina Paliativa

☐ Microbiologia

☐ Neurologia

☐ Oftalmologia

☐ Otorrinolaringologia

☐ Patologia

☐ Pediatria

☐ Psiquiatria/Psicossomática

☐ Radiologia

☐ Urologia

11. Em quais disciplinas pré-clínicas, na sua opinião, a Realidade Estendida (XR) tem maior potencial de utilização? *

- | | |
|-------------------------------------|--|
| ☐ Anatomia | ☐ Fisiologia |
| ☐ Biologia | ☐ Psicologia/Sociologia |
| ☐ Bioquímica | ☐ Química |
| ☐ Física | ☐ Semiologia |

12. Em que tipo de formato de ensino considera que a Realidade Estendida (XR) seria mais relevante? *

- ☐ Aula Teórica
- ☐ Aula Prática
- ☐ Seminário

13. Em que tipo de formato de avaliação considera que a Realidade Estendida (XR) seria mais relevante? *

- ☐ Exame Teórico
- ☐ Exame Prático

14. Quais as vantagens da Realidade Estendida (XR), na sua opinião? *

- | | |
|---|---|
| ☐ Amplas possibilidades de simulação | ☐ Representação de doenças raras |
| ☐ Aprendizagem interativa em primeira pessoa | ☐ Treino de raciocínio clínico |
| ☐ Cenários repetíveis | ☐ Sem vantagens |
| ☐ Melhoria de competências | |

15. Quais as desvantagens da Realidade Estendida (XR), na sua opinião? *

- | | |
|--|---|
| ☐ Experiência pouco realista | ☐ Suscetibilidade a erros técnicos |
| ☐ Problemas de saúde (tonturas, dores de cabeça, etc) | ☐ Sem desvantagens |
| ☐ Requisitos técnicos/competências | |

16. Até que ponto estas afirmações correspondem à sua opinião? *

1- Definitivamente Não; 2- Provavelmente Não; 3- Não Sei;
4- Provavelmente Sim; 5- Definitivamente Sim.

	1	2	3	4	5
a) A Realidade Estendida (XR) melhoraria o ensino médico					
b) Eu participaria numa disciplina que utilizasse a Realidade					
c) A Realidade Estendida (XR) tem enormes vantagens para mim					
d) A Realidade Estendida (XR) deveria ser integrada permanentemente nos currículos de medicina					
e) Consigo imaginar a observação visual de um paciente em Realidade Estendida (XR)					
f) Consigo imaginar a avaliação clínica de um paciente em Realidade Estendida (XR)					
g) Consigo imaginar comunicar com um doente em Realidade Estendida (XR)					
h) Consigo imaginar simulações de doentes holísticos e realistas num ambiente de Realidade Estendida (XR)					
i) Consigo imaginar trabalhar em equipa em Realidade Estendida (XR)					

17. Quão provável é, na sua opinião, que a Realidade Estendida (XR) influencie o ensino médico no futuro? *

1	2	3	4	5	6	7	8	9	10
Nada					Muito				
Provável					Provável				

18. Tem alguma ideia para cenários em Realidade Estendida (XR) que gostaria que fossem disponibilizados? Descreva por poucas palavras.

Figure B.1: Adapted survey used in the study.

Appendix C

Survey's Information Brochure

Objetivo

O principal objetivo deste estudo é compreender as perceções dos estudantes de medicina sobre o uso da realidade estendida no ensino médico, explorando como estas tecnologias podem ser integradas no currículo e na formação prática dos estudantes.



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A investigadora e a investigadora supervisora declaram não existir conflitos de interesse relacionados com este estudo de investigação.

Questionário: A Realidade Estendida no Ensino Médico



Voluntariedade de Participação

A PARTICIPAÇÃO NESTE ESTUDO É VOLUNTÁRIA.

Cabe ao participante decidir se aceita ou não o convite, sem qualquer tipo de obrigação, pressão ou impacto negativo. Caso decida participar, mantém o direito de desistir a qualquer momento, independentemente da fase em que se encontre no estudo, sem prejuízo nos seus direitos, nem no acesso a serviços, apoio ou oportunidades disponibilizados pela instituição ou pelos investigadores.

Metodologia

Este estudo, parte de uma Dissertação de Mestrado em Engenharia Biomédica, envolve a recolha de dados através de um questionário online, distribuído por e-mail institucional e presencialmente durante algumas aulas, utilizando a plataforma Microsoft Forms. As respostas serão posteriormente analisadas estatisticamente para explorar a utilidade da realidade estendida no ensino médico.

Proteção de Dados Pessoais

Privacidade

Os dados serão usados apenas para fins de estudo.

Confidencialidade

O questionário é anónimo e não serão solicitados dados identificativos.

Dados Pessoais

Os dados serão armazenados de forma segura e destruídos após a conclusão do estudo.



Este estudo foi aprovado pela Unidade de Proteção de Dados U.Porto e pela Comissão de Ética CHUdSA/ICBAS

Figure C.1: Brochure with information regarding the study.

Appendix D

Article Adaptation

Extended Reality (XR) and Its Role in Medical Education: A Survey

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Abstract—As Extended Reality (XR) technologies gain relevance in healthcare and medical education, understanding student perceptions is critical for effective integration. This study investigates undergraduate medical students' views on the utility, effectiveness, and barriers associated with XR in learning environments. A cross-sectional survey was conducted at ICBAS, collecting both quantitative and qualitative data. Statistical analysis and a word cloud synthesis of open-ended responses revealed that students generally perceive XR positively, particularly in areas requiring spatial understanding, procedural skills, and immersive simulation, such as anatomy, surgery, and emergency medicine. However, many respondents demonstrated limited familiarity with XR, primarily associating it with informal experiences like gaming. Students preferred experiential, hands-on learning and showed greater acceptance when XR aligned with educational goals. Perceptions varied by academic year, with earlier-year students valuing theoretical reinforcement and senior students emphasizing clinical realism. While XR was seen as beneficial for visualization and simulation, concerns persisted regarding its limitations in developing interpersonal competencies. Thus, the study recommends a phased implementation of XR in medical curricula, starting with foundational literacy and progressing to discipline-specific applications. Future research should include educator perspectives and pilot studies to optimize curricular alignment. When applied thoughtfully, XR can complement traditional methods and enrich medical training.

Index Terms—Extended Reality, XR, Medical Students, Survey, Integration

I. INTRODUCTION

In recent years, Extended Reality (XR) technologies, including Augmented Reality (AR), Mixed Reality (MR) and Virtual Reality (VR) [1], have stood out as promising tools in medical education by their ability to offer immersive, interactive and risk-free training experiences. Specifically, VR creates a fully immersive digital environment that replaces the physical world [2], AR overlays digital elements onto the real environment [3], and MR combines real and virtual components, enabling real-

time interaction between them [4]. Thus, these technologies provide interactive environments where users are able to engage with digital content in a way that feels natural and immersive [5], when visualizing anatomical structures, practicing procedures, and engaging with clinical scenarios in a safe and controlled environment.

The growing interest in XR is, in part, a response to the limitations of traditional educational methods. While lectures, cadaver dissections, and clinical rotations, remain as the foundation to medical education, they often fall short in meeting modern demands. Clinical placements, for example, are limited by patient availability, ethical constraints, and unpredictable case exposure, factors that raise concerns regarding the preparedness of graduates [6]. These limitations were exacerbated during the COVID-19 pandemic, when lockdowns severely disrupted in-person teaching and patient interactions [7], highlighting the urgent need for alternative, technology-driven methods [7], such as XR technologies [8], to ensure continuity in medical education.

These challenges have emphasized the need not only for alternative methods, but for ones that enhance the effectiveness of existing educational strategies. In this context, XR has built upon the legacy of simulation-based learning by offering dynamic, real-time environments that respond to learners' actions. This interactivity promotes engagement and supports experiential learning, a model where students acquire knowledge through active participation and reflection, leading to deeper understanding [9]. Beyond realism, XR improves scalability, engagement, and cost-efficiency [10]. It supports diverse learning styles and allows for customized educational experiences that can be aligned with specific objectives. Studies have also shown that learners using immersive simulations often demonstrate better retention and understanding of complex concepts [11]–[15].

Despite its promise, XR adoption is not without challenges. High costs, technical requirements, and potential distractions must be considered [16]. Moreover, student acceptance is critical, as their perceptions directly influence how effectively XR can be integrated into their learning, so understanding these is therefore essential for successful implementation. Yet, current research on student attitudes toward XR in medical education remains limited, highlighting a gap between technological advancement and meaningful adoption in academic settings. Thus, this study aims to explore that gap and offer insights into how XR can best be aligned with the educational needs of future healthcare professionals.

II. METHODOLOGY

A survey was used to explore undergraduate medical students' perspectives on XR in medical education, with the data collected being categorical. This included both nominal variables and ordinal variables, captured through single-choice, multiple-choice, Likert scale, and rating scale items. These addressed students' familiarity with XR, perceived usefulness, accessibility, and willingness to integrate XR into their education. One open-ended question was also included to allow participants to share ideas and suggestions.

To implement the survey, the target participants were medical students enrolled at Instituto de Ciências Biomédicas Abel Salazar (ICBAS), Universidade do Porto (U.Porto). Eligible participants were those studying in any of the first six years of the medical program. A non-probabilistic voluntary sampling method was used, where faculty members at ICBAS were contacted and asked to forward the survey invitation to their students via email. Approximately 20.75% of all medical students enrolled in the 2024/2025 academic year completed the survey.

Before distribution, the survey instrument itself was carefully prepared to ensure its suitability for this context. It was adapted from a study by Mergen *et al.* on the integration of VR into medical curricula [17], and reviewed to align with the Portuguese medical education context. Some questions were added, divided, or reworded to improve clarity and relevance. The survey was translated into Portuguese, ensuring the integrity and meaning of the original questions were preserved. After, a pilot test was conducted with 29 medical students from other institutions, and feedback confirmed the survey's clarity, structure, and ease of understanding.

Following this process, data and ethical approvals were granted by the Unidade de Proteção de Dados da U.Porto and the Comissão de Ética do Centro Hospitalar Universitário de Santo António/ICBAS, respectively, succeeding the submission of required documentation, the full survey, and an informational brochure for review. Participation was voluntary, anonymous, and confidential, given that no personal data were collected. Participants were informed they could withdraw at any point before submission and informed consent was obtained when participants, after reading the study information, proceeded to complete and submit the survey.

Once ethical and data protection approvals were secured, data collection took place from early February to the end of April. The survey was distributed electronically via a link and QR code in the invitation email, where reminders were sent throughout the collection period via faculty members. The survey was hosted on Microsoft Forms, with an average completion time of 8 minutes and 7 seconds, and responses were stored in an Excel file on OneDrive linked to a licensed student account at Faculdade de Engenharia da Universidade do Porto, thus data were protected from unauthorized access and securely backed up.

Analysis was performed using IBM SPSS Statistics (version 30). Descriptive statistics summarized responses to closed-ended items, reporting frequencies and percentages, and inferential statistics provided understanding on associations between variables. Given that the data were nominal and ordinal, the chi-square test ($p < 0.05$) was used to assess associations between categorical variables. However, if requirements weren't met Fisher's exact test was conducted instead, and if dealing with large datasets Monte Carlo's significance test was used. For the open-ended item, a word cloud was generated to visually represent frequently mentioned terms, summarizing recurring concepts raised by students. While the analysis provided valuable insights, certain limitations must be acknowledged. The use of a non-probabilistic voluntary sampling method may have introduced selection bias, as students interested in XR may have been more likely to respond. Additionally, the focus on a single institution limits the generalizability of results. Lastly, the short data collection period may have led to underrepresentation of certain student groups, potentially skewing perceptions.

III. RESULTS

A. Sample and Demographics

In total, 226 undergraduate students completed the survey, accounting for the approximately 20.75% mentioned in the previous section (Section II). Regarding demographics, students were inquired on their age group, gender, and study year, as shown in Figure 1.

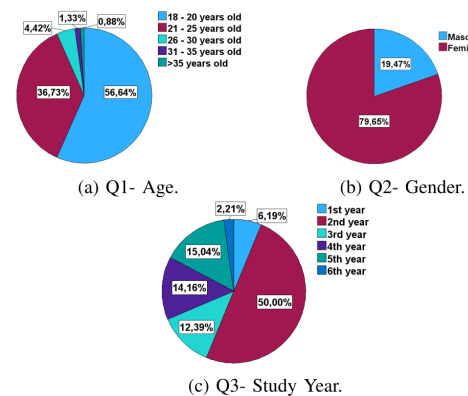


Fig. 1: Demographic characteristics of the study's population.

The majority of students ($n=113$, 50.00%) reported frequenting the 2nd year of medical school, aligning 56.64% ($n=128$) of participants being 18-20 years old, and 36.73% ($n=83$) being 21-25 years old. From the sample, an overwhelming 79.65% ($n=180$) of participants identified as female, while only 19.47% ($n=44$) stated being male.

B. XR Awareness and Prior Experience

When it came to knowledge of the term "Extended Reality (XR)", only 23.89% ($n=54$) of students indicated they were familiar with the concept, with 76.11% ($n=172$) affirming that they weren't aware of the term. Here, male students were significantly more likely than female students to report awareness of XR ($p=0.034$), where 29.55% ($n=13$) of male students recognized the term, compared to 21.67% ($n=39$) of females. Despite the low familiarity with the term "Extended Reality (XR)", awareness of individual technologies within it was visibly higher (Figure 2). Specifically, VR and AR were more familiar to students, with 211 respondents (93.36%) and 127 respondents (56.19%) reporting knowledge of these terms, respectively. MR remained as the least recognized one, with 17 respondents (7.52%) stating familiarity.

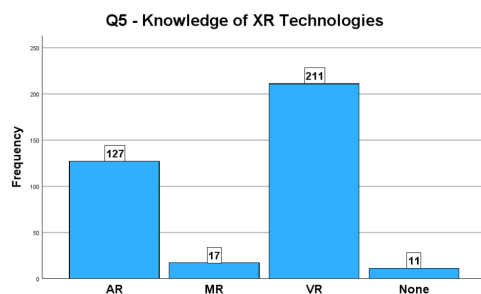


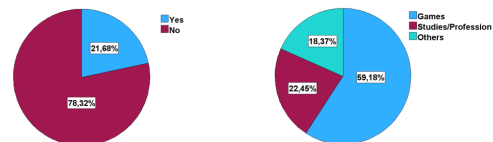
Fig. 2: Self-reported awareness of XR's technologies.

The only association found was between gender and knowing MR ($p=0.009$), as male students ($n=7$, 15.91%) were more likely to be familiar with it, than female students ($n=9$, 5%).

Nonetheless, a majority of students ($n=129$, 57.08%) reported that they were unable to distinguish between the three primary XR modalities, whereas 42.92% ($n=97$) indicated they could. Across different years of study ($p=0.048$), students were more or less likely to report being able to distinguish XR types: 1st ($n=9$, 64.28%), 3rd ($n=17$, 60.71%), and 5th ($n=17$, 50.00%) year students were more familiar with the different technologies within XR. On the other side, 2nd ($n=39$, 34.51%) year students were less likely to have the ability to distinguish between AR, MR, and VR.

When it comes to the actual use of XR (Figure 3a), experience was limited with only 49 respondents (21.68%) stating having ever used any form of XR technology, given that the majority of students ($n=177$, 78.32%) had never had previously interacted with XR technologies. Among experienced students,

three contexts in which they had used XR were explored (Figure 3b): games ($n=29$, 59.18%), studies/profession ($n=11$, 22.45%), and others ($n=9$, 18.37%).



(a) Q7- Previous XR Experience. (b) Q8- Origin of XR Experience.

Fig. 3: Reported XR experience and context of XR use.

Prior use varied significantly by gender ($p=0.047$), with 25.00% ($n=11$) of males students having previous experience with XR technologies, and only 20.00% ($n=36$) of female students. Coincidentally, respondents who reported being familiar with the concept of XR were more likely to have previously experience with these technologies ($p<0.001$, $n=36$, 66.67%), than those who weren't aware of the term ($n=27$, 15.70%), and to be able to distinguish between the three main technologies ($p<0.001$ and $n=36$, 37.11%), oppositely to those who couldn't distinguish between them ($n=13$, 10.08%).

C. Perceived Utility and Format Preferences

A large majority of participants agreed with the idea that XR could be a useful tool in medical education. Specifically, 211 out of 226 respondents (93.36%) agreed that XR technologies could be useful in medical education, while only 15 participants (6.64%) disagreed with the statement.

Next, to explore which subject areas students considered most appropriate for XR use, respondents selected specific disciplines from clinical domains (Figure 4). The most favored course was surgery with 93.36% ($n=211$) of students choosing it as a course with high potential for the utilization of XR. Following it, radiology ($n=119$, 52.65%), emergency medicine ($n=115$, 50.88%), neurology ($n=108$, 47.79%), and forensic medicine ($n=99$, 43.81%) were also highly selected options. Less frequently mentioned courses included palliative medicine ($n=34$, 15.04%), pharmacology ($n=34$, 15.04%), microbiology ($n=32$, 14.16%), and infectiology ($n=30$, 13.27%).

Q10- Student's Clinical Subject Preferences for XR

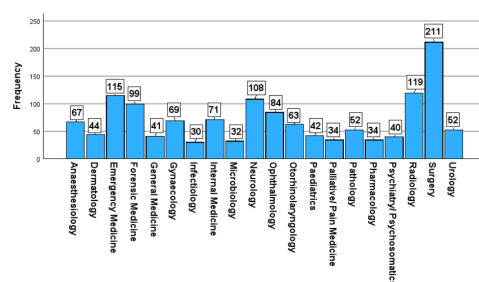


Fig. 4: Preferred clinical disciplines for XR integration.

Significant associations were found between participants' age group and preferences for anesthesiology ($p<0.001$), gynecology ($p=0.031$), emergency medicine ($p<0.001$), forensic medicine ($p=0.001$), and microbiology ($p=0.041$). The 21–25 age group was overrepresented in anesthesiology ($n=38$, 45.78%), emergency medicine ($n=56$, 67.47%), and gynecology ($n=34$, 41.00%), while the 18–20 group was underrepresented in these fields. Small overrepresentations occurred in the 31–35 group for gynecology ($n=2$, 66.67%) and microbiology ($n=2$, 66.67%). No students aged 26–30 or over 35 selected Forensic medicine despite expected counts. Year of study was associated with preferences for anesthesiology ($p=0.009$), gynecology ($p=0.019$), emergency medicine ($p=0.007$), and urology ($p=0.019$). 1st year students were underrepresented in anesthesiology ($n=1$, 7.14%) and emergency medicine ($n=4$, 28.57%), while 4th and 5th year students were overrepresented across these fields. Interest in urology peaked in 5th year students ($n=16$, 47.06%), with 2nd year students underrepresented. In gynecology, 4th year students matched expected values ($n=16$, 50%), while 1st and 2nd year students selected it less than expected. A significant association also existed between belief in successful XR integration and interest in surgery ($p=0.011$). Among students who didn't believe in XR integration, 11 of 15 (73.33%) selected surgery, while among those who did believe, 200 of 211 (94.79%) selected surgery. No significant associations were found between discipline preferences and XR familiarity, prior XR experience, or context of XR use.

Regarding preclinical specialties (Figure 5), anatomy had the majority of the votes with 198 (87.61%). Physiology ($n=128$, 56.64%) was in second place, and terminology ($n=120$, 53.10%) a close third. The least selected options were biochemistry with 33 votes (14.60%), and biology and psychology/sociology, both with 22 votes (9.73%).

Q11- Student's Preference on Preclinical Subjects for XR Use

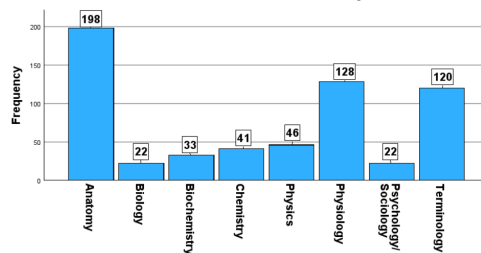


Fig. 5: Student's preclinical disciplines choices for XR integration.

Associations between preferences and participant characteristics varied across variables. A weak to moderate association was observed between gender and interest in anatomy ($p=0.046$). Male students showed greater interest than expected by chance ($n=43$, 97.73%), while female students had a more balanced distribution ($n=153$, 85.00%), slightly lower than expected. An association was also found between year of study and

preference for physiology ($p=0.045$). 1st year students showed slightly less interest than expected ($n=6$, 42.86%), and 2nd year students showed greater interest ($n=72$, 63.72%). Other years followed expected distributions, except for 6th year students, none of whom selected physiology. Finally, an association was found between year of study and preference for terminology ($p=0.026$). 3rd year students showed more interest than expected ($n=21$, 75.00%), while 1st year and 5th year students selected it less often than anticipated ($n=4$, 28.57%; and $n=13$, 38.24%, respectively).

On the subject of preferred instructional formats for XR use, students identified practical classes as the most relevant for XR integration ($n=187$, 82.74%). This was followed by seminars ($n=29$, 12.83%), and finally by theoretical classes ($n=10$, 4.42%). A statistically significant association was found between XR integration perception and teaching format preference ($p=0.036$). Students who reported that XR integration would not be useful ($n=15$) showed higher-than-expected preferences for seminars ($n=4$, 26.67%) and theoretical classes ($n=2$, 13.33%), while those who saw XR as useful ($n=211$) selected practical classes more often than expected ($n=178$, 84.36%). For evaluation formats, the overwhelming majority ($n=218$, 96.46%) of respondents chose practical exams as the best choice for XR integration, while only 8 respondents (3.54%) disagreed and chose theoretical exams. No associations were found between any of the variables and preferred evaluation format.

D. Opportunities and Challenges of XR in Medical Education

Main potential advantages and disadvantages of integrating XR into medical education were also assessed (Figure 6). The top three chosen advantages were broad simulation possibilities ($n=209$, 92.48%), closely followed by interactive first-person learning ($n=186$, 82.30%), and competence improvements ($n=166$, 73.45%). The options of depiction of rare decisions ($n=92$, 40.71%) and repeatable scenarios ($n=95$, 42.04%) were less chosen, each with under 100 votes. Consequently, overall students only saw advantages on the integration of XR into their education, as "No Advantages" was only chosen three times (1.33%).

Q14- Student-Reported Advantages of XR in Medical Education

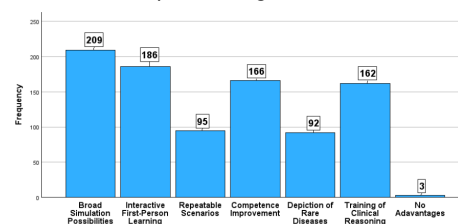


Fig. 6: Advantages of XR in medical education as reported by students.

Associations between perceived advantages and participant characteristics showed no significant relationships for age, gen-

der, XR familiarity, prior XR experience, or preferred teaching format. A significant association was found between year of study and the benefit representation of rare diseases ($p=0.020$): 3rd year students agreed more often than expected ($n=17$, 31.48%), as well as 4th year students ($n=17$, 53.13%), while 5th year students agreed less often than expected ($n=9$, 26.47%). Ability to distinguish VR, AR, and MR was significantly associated with broad simulation possibilities ($p=0.029$): students who could distinguish these modalities surpassed projected agreement levels ($n=54$, 100%). This ability was also associated with improvement of competencies ($p=0.018$): distinguishers concurred more frequently than anticipated ($n=79$, 65.18%). Origin of XR experience showed a significant association with repeatable scenarios ($p=0.019$): students with gaming experience were in greater agreement than presumed ($n=14$, 28.57%). Perception of successful XR integration was associated with broad simulation possibilities ($p=0.018$): those who saw XR as integrated agreed more often than expected ($n=198$, 90.99%). It was also associated with training of clinical reasoning ($p=0.014$), where those who saw successful integration found unexpected common ground ($n=156$, 71.13%). Finally, evaluation format showed a significant association with improvement of competencies ($p=0.033$), given that students preferring XR on practical exams exhibited unexpected alignment ($n=163$, 74.77%).

Turning to concerns (Figure 7), technical error susceptibility topped the list with 141 students (62.39%) choosing it as their main reason for distrust in XR. Technical requirements/competencies was next ($n=109$, 48.23%), followed by health problems ($n=74$, 32.74%) and unrealistic experience ($n=64$, 28.32%). A minority of 15 students (6.64%) reported no disadvantages.

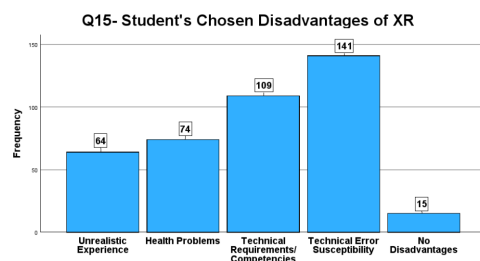


Fig. 7: Student's reported disadvantages of XR technologies.

A significant association was found between age group and the perceived disadvantage "technical errors or malfunctions" ($p=0.011$). Among students aged 18–20, more than expected selected this drawback ($n=89$, 69.53%). Students aged 21–25 showed a slight opposite trend, selecting it less often than expected ($n=47$, 56.63%).

E. Attitudes Towards XR in Medical Education

In the final set of close-ended items, participants were asked to express their overall attitudes toward XR in medical

education on several subquestions using a 5-point Likert scale (1="Definitely Not" to 5="Definitely Yes") (Figure 8). The nine statements addressed perceptions of XR's benefits, potential curricular integration, and the imagined application of XR to various clinical activities.

Most students agreed XR would improve education ($n=197$, 87.17%) and were interested in XR-based courses ($n=212$, 93.81%). XR use for visual ($n=178$, 78.76%) and clinical ($n=160$, 70.80%) exams was seen as imaginable by many, though fewer could imagine XR-based patient communication ($n=78$, 34.51%). Agreement for XR teamwork and holistic simulations stood at 63.72% ($n=144$).

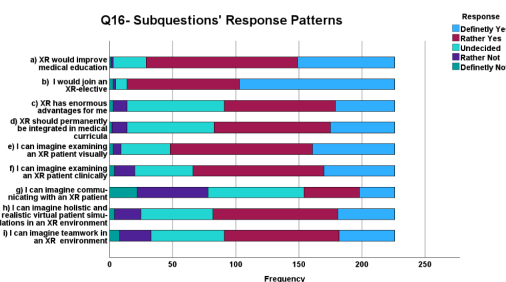


Fig. 8: Distribution of responses across survey items rated on a 5-point Likert scale.

Statistical analysis revealed that gender was significantly associated with two items. For item a) ($p=0.029$), female students were more likely than expected to believe XR would improve medical education (161 vs. 156.9). For item i) ($p=0.039$), male students were more likely to select "Definitely Yes" (12 vs. 8.6). Year of study also showed associations: for item b) ($p=0.041$), 1st year students were more likely to choose "Definitely Yes" (11 vs. 7.6), while 2nd year students were more often undecided (6 vs. 4.5), and 4th year students leaned towards "Rather Not" (2 vs. 0.3). For item c) ($p=0.017$), 1st year students showed higher-than-expected agreement ("Rather Yes" 7 vs. 5.5), and also some doubt ("Rather Not" 3 vs. 0.7); 2nd year students had a strong overrepresentation in "Undecided" (44 vs. 38.5); 4th year students were elevated in both "Rather Not" (4 vs. 1.6) and "Definitely Yes" (8 vs. 6.7); 5th year responses were close to expected; 6th year students were polarized, with overrepresentation in "Definitely Not" (1 vs. 0.1) and "Definitely Yes" (2 vs. 1.0). Students' beliefs about the potential success of XR integration in education were also related to item a) ($p=0.001$). Those doubtful about XR's success over-selected "Rather Not" (2 vs. 0.1) and "Undecided" (5 vs. 1.7), while those confident in XR's success were more likely to respond with "Rather Yes" (117 vs. 112.0). Preferred class format was linked to responses on multiple items. For item a) ($p=0.002$), students favoring practical classes were more likely to select "Definitely Yes" (69 vs. 63.7); those favoring theoretical classes were overrepresented in "Undecided" (6 vs. 1.2) and had no responses in "Definitely Yes" (expected: 3.4).

For item b) ($p=0.004$), practical class supporters again over-selected “Definitely Yes” (107 vs. 101.8), while theoretical learners under-selected this response (1 vs. 5.4) and over-selected “Undecided” (2 vs. 0.4). In item c) ($p=0.016$), seminar-preferring students over-selected “Rather Not” (3 vs. 1.4) and “Rather Yes” (15 vs. 11.3); theoretical learners again showed elevated “Undecided” (9 vs. 3.4); practical class supporters had a slight overrepresentation in “Definitely Yes” (44 vs. 38.9). Item e) ($p=0.019$) followed a similar pattern, with practical class students overrepresented in “Definitely Yes” (62 vs. 53.8), while theoretical learners again lacked strong agreement (0 vs. 2.9) and leaned toward “Undecided” (3 vs. 1.7). For item f) ($p=0.033$), practical class students were slightly more likely to select “Definitely Yes” (53 vs. 46.3), while seminar students leaned toward “Rather Yes” (19 vs. 13.3). In item h) ($p=0.004$), practical learners favored “Definitely Yes” (42 vs. 37.2); seminar learners selected “Rather Not” more than expected (7 vs. 2.7); theoretical students again showed no “Definitely Yes” responses (expected: 2.0). Similarly, for item i) ($p=0.036$), practical learners were more likely to respond with “Definitely Yes” (41 vs. 36.4), while theoretical class supporters over-selected “Undecided” and “Definitely Not,” and provided no “Definitely Yes” responses. Preferred exam format was also significantly associated with responses. For item a) ($p=0.004$), students preferring theoretical exams were much more likely to be uncertain (5 “Undecided” vs. 0.9). Practical exam supporters had response counts close to expected, with a high number confidently agreeing XR would improve education (118 “Rather Yes” and 76 “Definitely Yes”). For item b) ($p=0.003$), theoretical exam supporters were more likely to choose “Rather Not” (1 vs. 0.1) and “Undecided” (2 vs. 0.3), while practical exam supporters again aligned closely with expectations (combined “Rather Yes” and “Definitely Yes”: 207 vs. 204.4).

Having given their opinion on the current educational value and integration of XR, students were then asked to estimate how likely they believed XR technologies were to influence the future of medical education (Figure 9). The most frequent ratings were 8 (32.3%), 7 (22.6%), 10 (15.9%), and 9 (14.6%). Ratings below 5 were rare, with only 1 participant (0.4%) rating a 3, and small percentages selecting 4 (2.2%) or 5 (2.7%). The cumulative percentage of ratings 7 or above reached 84.1%.

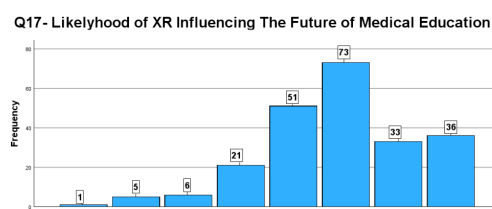


Fig. 9: Frequency distribution of participant ratings on the likelihood that XR technologies will influence the future of medical education.

Significant associations were found with two variables related to XR integration ($p = 0.002$) and class format ($p = 0.042$). Participants reporting no successful XR integration were overrepresented at rating 7 (7 vs. 3.4) but underrepresented at ratings 8 and 9 (1 vs. 4.8, and 0 vs. 2.2, respectively). Conversely, participants reporting successful XR integration were overrepresented at higher ratings of 8 and 9 (72 vs. 68.2, and 33 vs. 30.8) and underrepresented at rating 7 (44 vs. 47.6). Regarding class format, participants who chose seminar showed higher-than-expected frequencies at mid-range ratings 6 (6 vs. 2.7) and 7 (10 vs. 6.5), but were underrepresented at high-end ratings 8–10. Those who chose theoretical class were overrepresented at ratings 5 (1 vs. 0.3) and 6 (3 vs. 0.9), yet recorded no responses at ratings 7 and 10. Participants preferring practical classes for XR were overrepresented at top ratings 8 (63 vs. 60.4) and 10 (34 vs. 29.8), while underrepresented at rating 6 (12 vs. 17.4).

F. Proposed XR Scenarios in Medical Education

The survey’s final question invited participants to suggest XR scenarios they would like to see developed for medical education. Out of the total respondents, 32 provided answers ranging from single words to short phrases, with the most common words being summarized in Figure 10.



Fig. 10: Word cloud illustrating key terms from participant suggestions for XR-based scenarios in medical education.

A large number of responses centered around surgical training. Participants expressed interest in simulated operating room environments, surgical procedures, and technical practice. These suggestions often referred to the possibility of rehearsing complex surgeries and engaging with realistic clinical settings, highlighting surgery as a primary application for XR. Emergency medicine was another commonly mentioned area. Students identified the value of XR for simulating urgent care situations, allowing for experiential learning in scenarios that require quick thinking and decision-making under pressure.

Several participants mentioned clinical training uses beyond surgery and emergency care. These included ideas related to patient consultations, clinical case simulations, and procedural practice. Specific procedures, including punctures and blood gas analysis, were named as examples of tasks that could be

rehearsed using XR tools. A smaller set of responses touched on the role of XR in supporting early exposure to practical skills or enhancing self-guided study in the absence of physical materials. Additionally, one or two participants pointed out limitations of XR, expressing concern about its inability to replicate real patient interaction, especially for learning aspects that involve communication or empathy.

On the preclinical side, anatomy emerged as a significant area of interest, particularly in relation to the visualization of complex structures. Participants highlighted the potential of XR to support anatomical learning by offering detailed, three-dimensional views of internal systems that are difficult to fully explore through traditional methods. This included references to the study of organs, vessels, nerves, and bones. Some respondents also suggested disciplines such as biochemistry, pharmacology, and physiology. In these cases, XR was seen as a way to better visualize dynamic or abstract content, such as molecular interactions and physiological mechanisms.

IV. DISCUSSION

The study's participant demographics reflected a broad representation of medical students, predominantly young adults aged 18–25 and mostly female, consistent with current medical school enrollment trends. The majority were in early academic years, especially 2nd year students, meaning the findings mainly represent preclinical perspectives with limited clinical exposure. This distribution supports relevance across different cohorts but suggests less insight from advanced clinical experience.

Students showed low awareness of XR terminology, indicating that XR is not yet widely recognized as a unified concept in medical education. This reflects limited exposure or education on XR, which may hinder readiness to engage with these tools. Gender differences in XR familiarity paralleled general societal technology engagement patterns, highlighting the need for equitable access and encouragement. VR and AR were more familiar than MR, mirroring public exposure, but many students struggled to differentiate XR modalities, signaling conceptual confusion that could impair technology evaluation or selection. Gaming was the most common prior XR exposure context, suggesting informal, recreational engagement dominates. This points to a strong opportunity to integrate XR more systematically into curricula to provide meaningful, skill-building experiences. The relationship between XR use, familiarity, and modality distinction underscores the importance of hands-on exposure for building technological literacy and confidence. Medical programs could improve preparedness by enhancing awareness, offering accessible experiential learning, and clarifying XR distinctions and applications.

Students expressed openness to XR integration despite limited direct experience, with strong agreement on its potential value driven more by future expectations than hands-on knowledge. Preferences centered on XR's role in disciplines demanding spatial awareness, visualization, and procedural repetition, particularly clinical areas like surgery, radiology, and emergency medicine, as well as preclinical anatomy education. Preferences varied by academic progression: senior students

avored clinical applications, while earlier-year students leaned toward foundational topics, indicating evolving expectations from theoretical to practical uses. Practical classes and evaluations were preferred formats for XR, reinforcing its experiential strength. Even skeptical students preferred structured settings like seminars, suggesting hesitation stemmed more from pedagogical concerns than outright rejection. Students' perceptions of XR's educational advantages aligned with medical education goals, favoring immersive, simulation-based learning that enhances knowledge and clinical competence. While competence and engagement were recognized, less emphasis was placed on rare condition depiction or scenario repeatability, possibly reflecting limited curricular exposure. Intermediate-year students more often valued XR's representation of rare diseases, tied to growing clinical awareness. Familiarity with XR modalities correlated with greater appreciation of simulation benefits, suggesting conceptual clarity enhances perceived value. Positive perceptions also aligned with recognition of educational benefits like clinical reasoning support, implying institutional endorsement boosts confidence in XR's legitimacy.

Concerns were consistently about technical reliability and required proficiency, with younger students somewhat more sensitive to technical issues. Overall, while broadly supportive, students' views depended on educational stage, exposure, and technological familiarity, emphasizing the need to tailor XR integration to their evolving needs. Most students considered XR valuable and showed strong willingness to engage, particularly for visual and clinical examination of virtual patients. However, caution was noted regarding XR use for communication with patients and teamwork simulations, likely due to technological limitations or doubts about replicating complex interpersonal dynamics. This suggests XR development should focus on areas with clear perceived benefits while innovating to improve fidelity for collaborative education. Gender and academic year influenced perceptions: female students were slightly more optimistic, early-year students showed mixed views, and senior students were more cautious. Preferences for practical, hands-on learning correlated with greater XR receptiveness, while theoretical or seminar-oriented students were more reserved. Expectations for XR's future were optimistic, shaped by experiences of successful integration and preferred formats rather than demographics.

Students prioritized XR applications emphasizing practical skill acquisition in high-stakes fields like surgery and emergency medicine, recognizing XR's ability to simulate repeatable practice in these environments. This underscores XR's role in building clinical readiness beyond novelty. Interest also included routine clinical tasks, showing expectations for XR to support foundational skills. In preclinical education, XR's visualization of anatomy and biological processes was valued for translating abstract content into tangible learning. Concerns about XR's limitations in authentic patient interaction were prominent, highlighting that XR may not fully capture empathy and communication subtleties. This indicates a need for hybrid educational approaches combining XR with real patient

encounters.

In sum, XR technologies hold strong potential for spatial reasoning, procedural practice, and immersive simulation, especially in hands-on fields like surgery and emergency medicine, where repeatable practice fills gaps in traditional education. They also aid preclinical learning by visualizing anatomy and complex processes. However, students recognize XR's limits in replicating authentic patient interaction and communication, suggesting a need for hybrid approaches combining XR with real encounters. Limited familiarity calls for early, structured XR literacy, with expectations evolving from theory to clinical application as students advance. Preferences for practical formats and concerns about XR's interpersonal limitations indicate it should complement, not replace, real-world experience. Educators should focus on high-value applications and improve XR tools to support both practical and relational learning goals.

V. CONCLUSION

This study set out to investigate medical students' perceptions of integrating XR technologies, specifically AR, MR, and VR, into medical education, amid the growing interest in immersive tools for training future healthcare professionals. The research aimed to explore students' awareness, experiences, and expectations related to XR, while also identifying potential challenges and opportunities for its adoption.

To achieve this, a targeted survey was conducted at ICBAS, collecting data on students' conceptual understanding of XR, their practical exposure, and their views on its educational relevance. The findings revealed strong enthusiasm for XR, particularly in disciplines requiring spatial visualization and procedural practice, such as anatomy, surgery, and emergency medicine. However, students often struggled to distinguish between XR modalities, pointing to a need for structured XR literacy within the curriculum. While they recognized XR's value for immersive learning, concerns were raised about its current limitations in replicating interpersonal interactions and teamwork scenarios. These results suggest XR should be used to complement, not replace, real clinical experiences. Preferences for practical, hands-on learning formats and differing perceptions across academic years emphasize the need for adaptable implementation strategies.

Consequently, the study recommends a phased integration of XR technologies in medical education, beginning with early conceptual exposure and advancing toward more specialized applications. Ensuring accessible technology, institutional support, and alignment with student learning needs will be key to realizing XR's full potential as a pedagogical tool.

VI. FUTURE WORK

Future research should adopt a broader, multi-perspective approach to XR integration in medical education by including not only students but also medical educators and clinical instructors. Exploring teachers' attitudes, readiness, and challenges with XR will help identify critical factors for successful implementation and inform faculty training programs, fostering alignment between learner expectations and teaching practices

for a cohesive XR-enhanced environment. Additionally, practical experimental studies are needed to evaluate XR's real-world effectiveness through pilot programs using specific technologies, such as VR anatomy modules or AR-guided simulations, that assess student engagement, learning outcomes, and usability. These studies should combine quantitative and qualitative methods to capture XR's full educational impact, with special focus on its influence on technical skills and softer competencies like communication and teamwork, which were areas of skepticism among students. By bridging educator-learner perspectives and systematically testing XR tools in authentic settings, future work can improve technology effectiveness and promote sustainable adoption, ultimately advancing immersive and interactive learning experiences that better prepare medical professionals for clinical complexities.

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Figure D.1: Article adaptation of the current Master's dissertation.