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An augmented reality-based mobile learning environment for human anatomy education in elementary school

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ABSTRACT

Teaching human anatomy in elementary school can be challenging because anatomical structures are abstract and conventional resources provide limited opportunities for interactive visualization. This study developed and evaluated a mobile augmented reality (AR) learning environment for anatomy education. The system was developed using Unity, Vuforia, Blender, and AR Foundation following the analysis, design, development, implementation, and evaluation (ADDIE) instructional design methodology. A quasi-experimental study involved 70 elementary school students, randomly selected from the participating institution and distributed into control (n=35) and experimental (n=35) groups. The application integrated three-dimensional anatomical visualization, interactive assessments, immediate feedback, and learning analytics. A multidisciplinary panel of 50 experts evaluated usability, interactivity, learning effectiveness, and motivation. The experimental group improved from a mean pre-test score of 11.60 to 18.11, compared with an increase from 11.80 to 14.20 in the control group. The between-group comparison was statistically significant ($p<0.001$), with a large effect size (Cohen's $d=1.41$). Learning analytics showed progressive increases in quiz performance and student engagement throughout the nine-month intervention. These findings indicate that the proposed AR-based mobile learning environment can support anatomy education by integrating interactive visualization, assessment, feedback, and continuous learning monitoring.

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1. INTRODUCTION

Elementary school children show a keen interest in learning and are often surprised to discover how science works, especially when studying the human body. In this regard, teachers, aware of this natural curiosity, have been progressively preparing themselves to deliver more dynamic, meaningful, and student-centered lessons. Thus, their commitment aims not only to create a positive educational experience but also to strengthen students' holistic development and cognitive abilities [1]. Similarly, in today's educational context, the role of the teacher has evolved significantly, shifting from that of a mere transmitter of knowledge to a facilitator of learning who motivates, guides, and fosters scientific curiosity [2]. Consequently, this pedagogical transformation is supported by technological advances, which have driven substantial innovation in educational resources within the classroom. In particular, digital tools enhance traditional teaching through more visual, interactive, and immersive experiences, which promote a better understanding of complex concepts [3]. Consequently,

students are able to assimilate content more quickly and effectively, which contributes significantly to improved learning outcomes [4]. Furthermore, the integration of technologies such as augmented reality (AR) encourages active participation and self-directed learning, which helps create more dynamic and inclusive educational environments [5]. Similarly, these innovations foster a lasting interest in science and knowledge in general [6], thereby reinforcing students' intrinsic motivation.

Student attention is a key factor in ensuring effective learning. However, in many educational settings, students tend to be easily distracted by the many stimuli in their environment, making it difficult to maintain sustained concentration during academic activities. In this regard, teachers are required to implement innovative pedagogical strategies that allow them to capture and sustain students' interest, thereby promoting more meaningful learning [7]. Nevertheless, despite these efforts, it is sometimes difficult to fully meet all students' expectations or ensure optimal levels of attention throughout the entire class session [8]. Furthermore, children with learning difficulties present an additional challenge within the educational process, as they require differentiated approaches and specific strategies that address their particular needs [9]. Consequently, this situation requires teachers to develop adaptive and flexible pedagogical skills geared toward personalized learning. Likewise, the integration of emerging technologies and active methodologies has been identified as an effective alternative for improving students' attention, motivation, and participation in the classroom [10]. However, when teachers lack adequate resources and methodological support, they face high levels of work-related stress. As a result, this situation not only affects their professional performance but can also negatively impact their emotional well-being and the classroom environment [11]. Similarly, recent studies indicate that teachers' workloads and the lack of innovative pedagogical tools can directly influence the quality of the teaching-learning process [12].

There has been a notable increase in cases of low academic performance among children, a situation largely associated with the limitations of the teaching methods employed by some educators [13]. In this context, the lack of adequate teaching resources hinders the clear and effective transmission of content, which directly impacts the quality of learning [14]. As a result, students tend to lose interest during class, showing signs of demotivation, boredom, and distraction, which negatively affects their level of comprehension [15]. Similarly, self-directed learning has become a fundamental component of the educational process, as it allows students to continue acquiring knowledge and completing tasks independently [16]. However, this ability does not develop uniformly among all students, as some struggle to organize themselves, maintain focus, or understand the material without direct guidance from the teacher [17]. Therefore, this situation highlights the need to strengthen pedagogical strategies that promote the development of self-directed learning skills. In this regard, it is essential to incorporate innovative methodologies and educational resources that enhance both student motivation and active participation [18] in the learning process.

These evident problems in the educational context lead us to propose the implementation of AR in teaching about the human body. This proposal aims to generate a higher level of attention and motivation in children, while facilitating the understanding of complex content through visual and interactive experiences. Similarly, the use of this technology provides teachers with innovative tools that optimize knowledge transfer, reduce barriers to learning, and enable a more dynamic and effective teaching process tailored to today's needs. Despite the growing use of AR in educational settings, existing studies have predominantly focused on short-term interventions or specific learning contents, providing limited evidence on sustained AR-supported learning in elementary education. In particular, research on long-term AR applications for human anatomy learning remains limited, as does the integration of continuous learning analytics with interactive assessment and progress tracking. This gap highlights the need for learning environments that combine immersive anatomical visualization with sustained monitoring of student learning. Therefore, this study developed and evaluated a mobile AR-based learning environment for human anatomy that integrates interactive three-dimensional visualization, assessment modules, learning analytics, and progress tracking throughout a nine-month intervention.

2. LITERATURE REVIEW

This section presents the theoretical and conceptual foundations underlying the development of the proposed AR learning environment. It describes the main technologies, development tools, and programming frameworks used in the implementation of the educational application, including Unity, C#, AR Foundation, Vuforia, and Blender. In addition, this section reviews previous studies related to the use of AR in educational contexts, highlighting its impact on student motivation, interactivity, engagement, and learning effectiveness across various academic disciplines. The reviewed literature provides the pedagogical and technological foundation for the development of the proposed AR-based system for teaching human anatomy.

2.1. Theoretical foundations

This section describes the main technological components and software tools used in the development of the proposed AR learning environment. These technologies provide the technical foundation necessary to create interactive, immersive, and educational AR experiences for teaching human anatomy. The development process integrates various platforms and software frameworks that work together to facilitate the design, implementation, and visualization of AR content. First, Unity was used as the primary development engine due to its ability to create interactive applications in both two-dimensional and three-dimensional environments. Unity provides an integrated workspace where developers can design scenes, manage animations, incorporate audio and physics systems, and control the behavior of objects within a single project environment [19]. In addition, the engine primarily uses the C# programming language to implement application logic and user interaction features. One of Unity's most significant advantages is its cross-platform compatibility, including support for mobile devices, computers, and consoles, making it well-suited for AR educational applications [20]. Furthermore, Unity has become one of the most widely used engines for augmented and virtual reality (VR) development thanks to its flexibility and broad compatibility with external frameworks. To facilitate application programming and interaction management, C# was used as the primary programming language. C# is an object-oriented language developed by Microsoft within the .NET ecosystem and is commonly used for software development, mobile applications, and video games [21]. Its object-oriented structure allows developers to organize and maintain application code efficiently, improving scalability and readability. Additionally, its syntax is similar to that of other programming languages such as Java and C++, which simplifies development and integration processes. Due to its compatibility with Unity, C# plays a fundamental role in implementing application logic, user interactions, and AR functionalities within the proposed system [22].

To enable AR capabilities, AR Foundation was integrated into the project as the primary AR framework. AR Foundation acts as an intermediary layer between Unity and the AR technologies available on mobile devices [23]. Through this framework, developers can create a single AR application capable of running on different operating systems, such as Android and iOS. AR Foundation also integrates technologies such as ARCore and ARKit, which provide essential functionalities, including motion tracking, environmental understanding, and surface detection. As a result, the framework simplifies cross-platform AR development and reduces the need to create separate applications for different devices [24]. This interoperability makes AR Foundation an effective solution for creating scalable AR educational experiences. In addition, Vuforia was incorporated to enhance image recognition and object tracking capabilities within the AR environment. Vuforia is an AR development platform originally created by qualcomm and currently maintained by PTC [25]. Its primary goal is to recognize markers, images, and real-world objects in order to overlay digital elements—such as 3D anatomical models, animations, or multimedia content-onto the physical environment. Since Vuforia integrates easily with Unity, it facilitates the development of interactive, marker-based AR applications [26]. Thanks to its reliability and precision in object recognition, Vuforia has been widely adopted in educational, industrial, and training settings. Finally, Blender was used to create and prepare three-dimensional anatomical models integrated into the AR application. Blender is open-source software specialized in 3D modeling, animation, rendering, and visual effects production [27]. The platform offers comprehensive tools for object modeling, texturing, lighting, and animation within a unified development environment. In addition, Blender supports multiple export formats compatible with Unity and other development platforms, enabling seamless integration of digital assets into the AR system [28]. Thanks to its versatility, accessibility, and extensive modeling capabilities, Blender has become one of the most widely used tools in digital content creation and educational visualization projects.

2.2. Background

Teachers have employed various strategies to foster understanding among their students, and AR has established itself as an innovative tool that enriches classrooms by encouraging active participation, improving communication between students and teachers, and offering more engaging and effective learning experiences. The authors also expanded the methodological foundation for the use of AR in elementary education, specifically in the first grade of the New Ukrainian School, applying it in areas such as oral interaction, media, and linguistic phenomena. Through resources such as interactive art books, coloring pages, stickers, and AR-enhanced theatrical performances, the development of emotional intelligence, creative thinking, self-awareness, and cooperation among students was fostered. Additionally, different ways of integrating AR into children's literature were explored: visualization and interpretation of artistic images, interaction with literary characters, educational games, and theatrical activities. As the central product, an AR application based on Ukrainian folk

tales was developed, designed as a playful journey with interactive stations and tags that allow users to analyze, interpret, and emotionally experience the works, implemented using Unity and the Vuforia 1 plugin [29]. This research aims to contribute to the development of AR as a learning tool by creating a simple application that uses a qualitative approach and the marker-based tracking method. The result is an educational tool called AR Belajar Bagian Tangan, designed to help elementary school teachers and students learn the parts of the hand. The application can be used in both labs and classrooms, reinforcing the teacher's explanations and encouraging students to experiment with AR, which improves their understanding and develops their analytical skills [30].

The article addresses the teaching of computer networks in vocational education, highlighting their complexity, the diversity of teacher training, and the limitations of laboratories, which hinder practical application and affect learning outcomes. To address this problem, a three-dimensional learning environment using AR was developed with the Assembly Edu software, following the analysis, design, development, implementation, and evaluation (ADDIE) model. The study, based on observations, interviews, and questionnaires, used both qualitative and quantitative analyses to validate the tool. The results showed that the AR resource, evaluated by content and media experts, achieved a very high level of validity, while students found it useful for better understanding the topics and increasing their motivation. It is concluded that competency-based AR learning resources are effective and applicable in teaching computer networks in vocational education [31]. The research presents a review of the use of VR and AR in education, focusing on the design and implementation of the course "VR and AR Software Development" for science, technology, engineering, and mathematics (STEM) teachers. The course integrates the Unity environment for visual design, Visual Studio for programming, and AR/VR platforms such as Vuforia, along with development tools such as JavaScript, A-Frame, AR.js, Three.js, ARToolKit, and 8th Wall. It is structured into modules that cover both VR (game engines, physical interactions, 3D interface and positioning, user interaction, navigation, and an introduction to VR) and AR (setup in Unity 3D, development of photography projects, creation of training materials with Vuforia, and applications on emerging devices). The 16-week course offered tasks and performance patterns that promote the development of skills in the design and application of innovative learning tools. The results of the survey conducted among participants show improvements in these skills and highlight the need to increase class hours, reduce independent work, offer detailed methodological recommendations, and present more practical problems related to STEM disciplines as implementation perspectives. The article presents FaceMe, a social game featuring an AR-based virtual agent designed to support the emotional development of children with autism spectrum disorder (ASD). Through a virtual agent, tangible tools, and dynamic, multi-level game mechanics, FaceMe teaches basic facial expressions in social contexts and aims to improve children's communication and emotional skills. Empirical results show that using the game led to active social behaviors and a better understanding of facial expressions among participants with ASD. In addition, design guidelines are established for the development of virtual agents in AR environments, opening up new possibilities for creating educational games that support children's learning and inclusion [32]. Various studies have investigated the use of AR to enhance learning across different subject areas. One study explored the use of AR to improve vocabulary learning. The application was developed using Unity and Vuforia, allowing users to interact with 3D objects related to linguistic concepts. The development process followed the ADDIE instructional design model. The results showed increased engagement and improved comprehension through interactive visualization in AR [33].

In another study, an AR application was developed to facilitate the understanding of chemical concepts. The system was created using Unity, Vuforia, and Blender for 3D visualization. The research followed the ADDIE development model, which includes the phases of ADDIE. The results demonstrated improvements in conceptual understanding and in users' interaction with educational content [34]. Similarly, the research focused on developing an AR application to visualize anatomical structures. The development methodology followed the ADDIE model to structure the design and implementation process. Unity was used as the primary development environment, while Blender was used to create detailed three-dimensional anatomical models. The application allowed users to interact with 3D representations of anatomical structures via mobile devices. The results indicated that AR technology improves visualization and facilitates the understanding of complex biological structures [35]. Another study presented the design and evaluation of a marker-based AR system developed to facilitate the learning of geometry. The development process followed the 4D instructional model (define, design, develop, and disseminate). The AR application was implemented using Unity and the Vuforia SDK to generate interactive three-dimensional polyhedral models that were activated by visual markers. The system allowed users to explore geometric structures, manipulate 3D shapes, and visualize formulas through real-time interaction [36]. Additionally, a study investigated the development of an AR learning system designed

to support the teaching of geography. The research followed a software development methodology based on the waterfall model, which includes the stages of analysis, design, implementation, and testing. The AR application integrates virtual objects with real-world environments, allowing users to interactively explore the structure of the Earth's layers. The system was developed using Unity and 3D modeling tools to create visual objects displayed on mobile devices. The evaluation results indicated that AR-based learning media provided more engaging and interactive experiences compared to traditional educational materials [37]. Overall, these studies highlight that AR is a highly effective tool for enriching teaching processes. It fosters closer interaction between teachers and students, increases student motivation, and encourages active participation. The authors agree that its application directly contributes to improving educational quality by offering more dynamic and meaningful learning experiences. In line with these perspectives, this article focuses specifically on teaching the human body, demonstrating how the incorporation of AR can facilitate content comprehension, reinforce practical learning, and create a more engaging and innovative learning environment for students.

3. METHOD

This section describes the methodological process followed in the development and evaluation of the AR-based learning system for teaching human anatomy in elementary school. It presents the research design, the distribution of participants, and the application of the ADDIE instructional model throughout the different stages of the study. In addition, this section explains the development and implementation of the AR environment, including the system architecture, the interaction process, the assessment modules, and the learning analytics features. Finally, it presents the assessment instruments and statistical analysis procedures used to measure educational effectiveness, usability, interactivity, motivation, and the learning outcomes achieved during the intervention.

3.1. Research design and participants

This study employed a quasi-experimental research design to evaluate the effectiveness of a mobile AR learning application for teaching human anatomy in elementary school. The study involved 70 students aged 10 to 12 years, who were randomly selected from the participating educational institution and distributed equally between a control group (n=35) and an experimental group (n=35).

Ethical considerations. Participation in the study was voluntary. Prior to student participation, verbal consent was obtained from the parents or legal guardians of the participating students. The collected information was handled confidentially, no personally identifiable information was reported, and the data were used exclusively for research purposes. The control group received conventional instruction based on textbooks and teacher explanations, whereas the experimental group used the proposed AR learning environment during the intervention.

Random selection was used to reduce selection bias and provide a more representative sample of the participating students. Both groups followed the same anatomy learning objectives and assessment procedures, while the main difference between them was the learning environment used during the intervention.

In addition, a multidisciplinary panel of 50 experts participated in the evaluation of the proposed system. The panel comprised 10 science teachers, 10 biology teachers, 10 software engineers, 10 UX/UI specialists, and 10 educational technology specialists. The experts evaluated the system according to four dimensions: usability, interactivity, learning effectiveness, and motivation and satisfaction. These dimensions were assessed using a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree).

The independent variable was the AR-based mobile learning application, while the dependent variables included attention, motivation, usability, interactivity, and learning effectiveness. These variables were assessed through academic tests, user surveys, expert evaluations, and interaction data collected from the application.

3.2. Analysis, design, development, implementation, and evaluation

ADDIE is a methodology used to plan and organize the development of educational content. This model consists of five stages: analysis, design, development, implementation, and evaluation. In the analysis phase, the needs and the context in which the project will be carried out are identified. Subsequently, in the design stage, the structure of the content, the activities, and the necessary resources are defined [38]. Next, the process moves to the development phase, in which the materials and tools to be used are created. Subsequently, the content is implemented in the intended environment. Finally [39], the evaluation phase is carried out to review the results and make improvements where necessary, as shown in Figure 1.

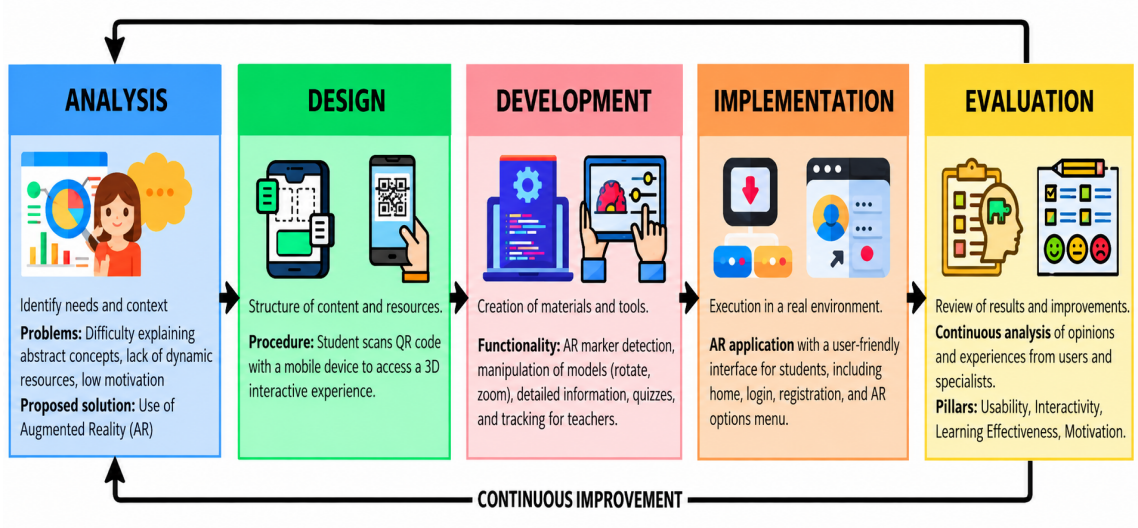


Figure 1. Application of the ADDIE methodology guiding the development and implementation of the proposed AR-based learning environment

3.2.1. Analysis

In this phase, we analyzed the main challenges teachers face in capturing and maintaining students' attention while teaching lessons on the human body [40]. These challenges include the difficulty of explaining abstract concepts, the lack of dynamic teaching resources, and low student motivation in traditional classrooms. We also analyzed the effects of these challenges, such as distraction, low participation, and superficial understanding of the topics. To address this situation, we proposed innovative solutions based on the use of AR, which provides more engaging interactive and visual resources. This technology allows students to observe and manipulate three-dimensional models in real time, fostering an active learning experience. The problems and their respective solutions are presented in an organized manner in Table 1 [40]–[45].

Table 1. Challenges in human anatomy education and corresponding AR-based solutions

Problem	Description	Possible solution
Difficulty visualizing internal structures	Students have difficulty understanding the organs and bones of the human body, as these structures are not visible from the outside. When relying solely on flat images or theoretical explanations, their ability to visualize the shape, size, location, and internal arrangement is limited, leading to a superficial understanding, and in many cases, conceptual confusion [41].	Use of 3D models in AR that allow for real-time visualization of structures such as the heart, brain, pelvis, and bones using markers.
Abstract learning of the human body	Teaching about the human body is often based on theoretical content that does not clearly represent the spatial organization of organs and systems. This makes it difficult for students to understand how the different parts of the body are interconnected, causing the learning process to be perceived as abstract and meaningless [42].	The implementation of AR with markers that project interactive three-dimensional models facilitates more visual and concrete learning.
Limited student interaction	In many educational settings, students take on a passive role in the teaching-learning process, merely listening to the teacher or observing materials without actively participating. This lack of interaction reduces exploration, curiosity, and the independent construction of knowledge, which negatively affects meaningful learning [43].	Development of an AR application that allows students to independently explore different parts of the human body.
The lack of dynamic visual resources	Traditional resources, such as books or printed diagrams, present information in a static manner, which prevents the observation of movement, changes, or anatomical details. This limitation hinders deep understanding and restricts students' ability to manipulate or explore the content [44].	The integration of interactive 3D models in AR with rotation, zoom, and detailed viewing features to enhance exploration.
Difficulty maintaining attention	Students, especially in the early grades, have a limited attention span, which is further compromised when lessons lack engaging and dynamic visual elements. The absence of interactive stimuli can lead to disinterest, distraction, and lack of concentration during class [45].	Use of an AR app with an engaging visual interface that captures attention through real-time visualization of organs and bones.

3.2.2. Design

This phase focuses on structuring the interaction processes that enable users to access the AR learning environment and interact with it effectively. In addition to defining the system's functionality, this stage establishes the instructional flow through which the study's pedagogical objectives are achieved [46]. Figure 2 illustrates the workflow of the AR learning process implemented in this study. The process begins with the instructor preparing the educational materials and QR codes. Subsequently, students access the mobile app, scan the QR codes, and view three-dimensional anatomical models in real time. Through interactive features such as rotation, zoom, and structure exploration, students actively engage with the learning content. Finally, the system integrates quizzes, immediate feedback, and learning analytics, allowing teachers to monitor students' progress through a dedicated dashboard.

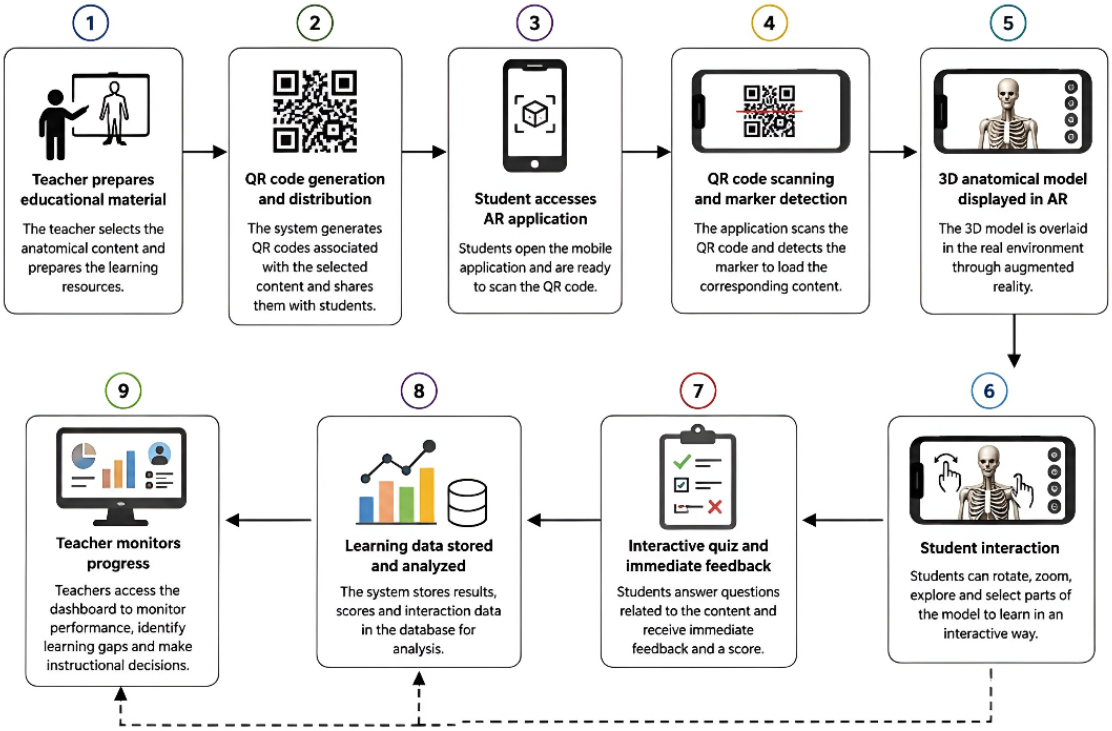


Figure 2. Workflow of the AR learning process for teaching human anatomy

3.2.3. Development

The AR learning environment was developed using an integrated framework combining 3D modeling, AR, and interactive learning features [47]. As illustrated in Figure 3, the system comprises three layers: input, processing, and interaction and visualization. The input layer captures real-world information through the mobile camera and detects AR markers or QR codes. The processing layer manages marker recognition, tracking, rendering, and manipulation of the three-dimensional anatomical models. The interaction and visualization layer provides students with access to interactive 3D models, anatomical information, quizzes, and immediate feedback. A teacher dashboard was also incorporated to monitor student performance and learning progress.

The learning analytics module recorded quiz responses, quiz performance, completed activities, and interaction with the three-dimensional anatomical models. Since the application operated offline, these data were stored locally and associated with the corresponding student profile. Learning progress was monitored using accumulated quiz results and completed activities.

The technical environment was standardized throughout the intervention to provide a consistent execution environment. The application was deployed on Samsung Galaxy A54 mobile devices running Android 13 with 6 GB of RAM. Unity 6 was used as the development engine, while Vuforia 10 and AR Foundation 6 supported AR functionality. Blender 5.2 LTS was used to create and prepare the three-dimensional anatomical

models. The application operated without an Internet connection during learning sessions, with AR content, quizzes, and student records processed locally. The main technical specifications are summarized in Table 2.

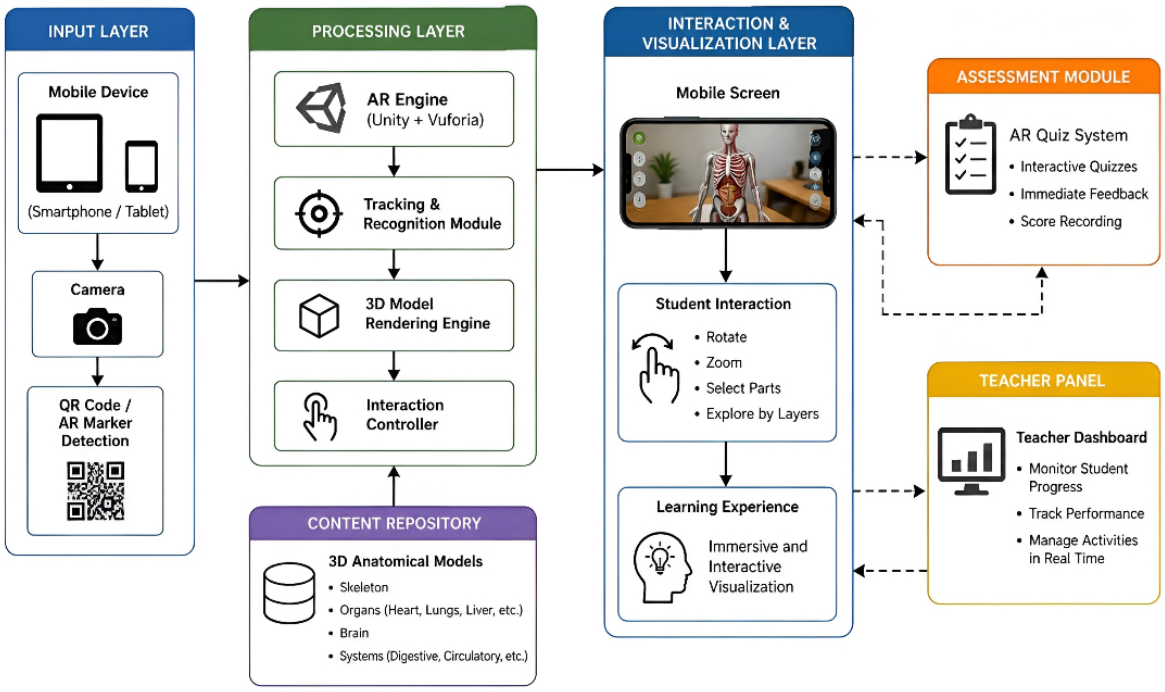


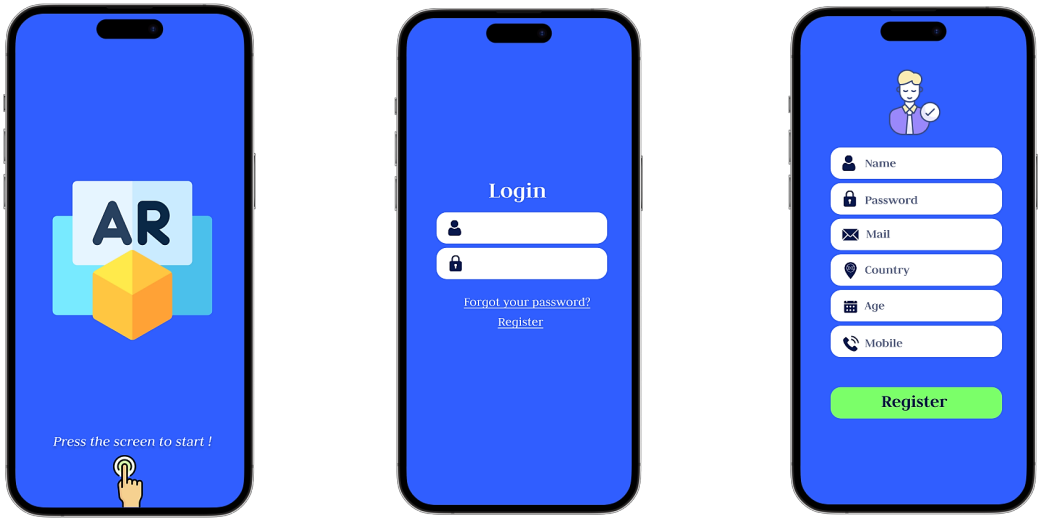
Figure 3. Architecture of the AR learning environment and interaction process

Table 2. Technical environment used for the AR application

Mobile device	Samsung Galaxy A54
Operating system	Android 13
RAM	6 GB
Development engine	Unity 6
AR framework	Vuforia 10 and AR Foundation 6
3D modeling software	Blender 5.2 LTS
Internet requirement	Not required during learning sessions
Data storage	Local storage

3.2.4. Implementation

The implementation phase of the ADDIE methodology synthesizes the work carried out in the previous stages, transferring the proposals to the real-world application context to verify their functionality and pedagogical relevance [48]. In this case, the AR system was used in an educational setting, resulting in an accessible and user-friendly interface for students. Figure 4 shows the application's initial interface, which covers both the access phase and the user login process. First, Figure 4(a) shows the mobile application's welcome screen, which serves as the entry point to the system; at this stage, the user must tap the screen to continue. Next, Figure 4(b) shows the login interface, where users must enter their previously registered credentials to access the app. Figure 4(c) illustrates the mobile app's user registration interface, designed to streamline the account creation process. On this screen, users must provide basic personal information, including name, password, email address, country, age, and mobile number. Additionally, the interface features a clear and well-structured design, complemented by representative icons that facilitate the identification of each input field. Finally, there is a sign-up button that allows users to complete the account creation process, contributing to an intuitive and user-friendly experience.



(a) (b) (c)

Figure 4. User access interface of the AR learning platform; (a) welcome screen, (b) authentication module, and (c) user registration interface for personalized learning and progress tracking

Figure 5 shows the AR options available in the app, designed to help students (especially children) learn about the different parts of the human body. Through this interface, users can select various anatomical elements, such as the bones of the hand, the femur, the pelvis, the thorax, the heart, and the brain, which can be explored using AR technology. In addition, the interface displays relevant user information, such as the registered child's name and age, enabling a more personalized learning experience. Overall, this design promotes interactive and dynamic learning by allowing users to actively explore anatomical structures in an intuitive way.

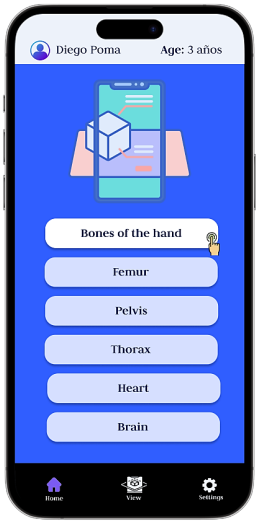


Figure 5. Anatomical exploration module within the AR environment

Figure 6 shows the mobile app in action, using AR technology to display the developed content. As can be seen, scanning a QR code projects three-dimensional models of different parts of the human body, including the bones of the hand, the femur, the pelvis, the thorax, the heart, and the brain. In addition, each model can be viewed within the real environment, allowing users to explore it from different perspectives, which facilitates a better understanding of anatomical structures. Thus, the implementation demonstrates the proper functioning of the developed system, as well as its potential to promote a more interactive, dynamic, and meaningful learning experience for students.

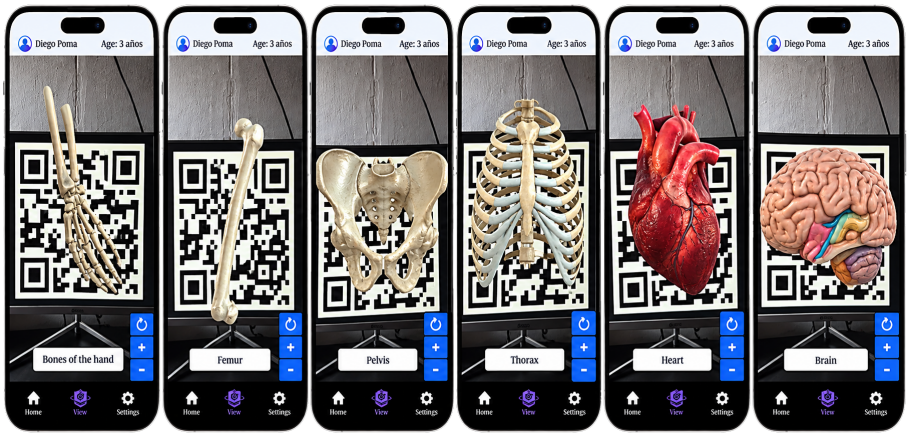


Figure 6. AR of the parts of the human body

Figure 7 shows the assessment module integrated into the AR application. Through this interface, students can take interactive quizzes related to the anatomical content studied during the learning sessions. The system provides immediate feedback, indicating correct and incorrect answers, and records individual scores. This feature plays a key role in reinforcing learning outcomes, as it allows students to assess their understanding in real time and encourages continuous learning. Additionally, the collected data is made available through the instructor's dashboard, enabling teachers to monitor student performance and identify learning gaps.

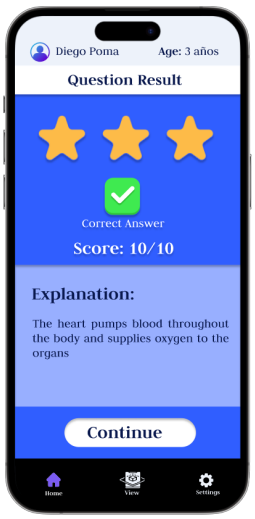


Figure 7. Interactive assessment module integrated into the AR learning environment

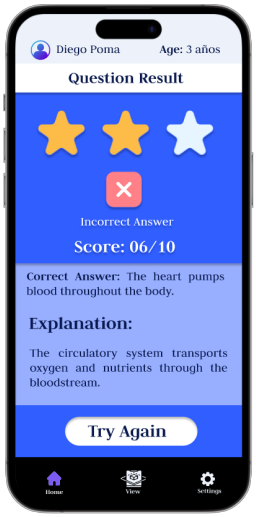
After submitting the questionnaire, the application provides immediate feedback to reinforce the learning process and maintain students' active engagement, as shown in Figure 8. As illustrated in Figure 8(a), the system displays a confirmation message when the student selects the correct answer, along with the score obtained and a brief explanation that reinforces conceptual understanding of the content covered. In contrast, Figure 8(b) shows the feedback mechanism that is applied when the student selects an incorrect answer. In this case, the system not only indicates the error through visual cues but also provides the correct answer accompanied by an explanatory message designed to reinforce learning. Furthermore, this feature allows students to identify errors in real time, reinforce conceptual understanding, and promote self-regulated learning. Similarly, the immediate feedback mechanism helps increase motivation, engagement, and continuous interaction throughout educational activities.

Figure 9 shows the student progress tracking interface integrated into the AR application. As illustrated in Figure 9(a), the system provides a detailed history of completed activities and quiz scores, allowing students

to review their academic performance over time. This interface displays relevant information, such as completed assessments, scores obtained, and learning achievements throughout the intervention period. On the other hand, Figure 9(b) presents the progress tracking module, which incorporates visual indicators and performance statistics to facilitate the identification of strengths and learning difficulties. These analyses allow both students and teachers to continuously monitor learning progress and assess the level of content comprehension achieved during educational activities. From a pedagogical perspective, this feature contributes to self-regulated learning by encouraging students to monitor their own academic progress and remain actively engaged throughout the learning process. At the same time, it allows teachers to monitor student performance and make informed pedagogical decisions based on the collected learning analytics.



(a)



(b)

Figure 8. Immediate feedback interface of the AR application; (a) correct answer response and (b) incorrect answer response with explanatory feedback



(a)



(b)

Figure 9. Student progress monitoring interface; (a) learning dashboard and (b) academic performance history throughout the intervention period

Figure 10 shows the teacher dashboard integrated into the AR learning system. This module allows teachers to monitor students' academic performance, access quiz results, and oversee classroom activities in real time. Through this interface, teachers can identify students with learning difficulties, assess participation levels, and track progress throughout the intervention period. In addition, the dashboard provides access to performance statistics, including average scores, completed activities, and attention indicators, facilitating data-driven pedagogical decision-making. This functionality reinforces the system's pedagogical value by supporting personalized learning and continuous assessment within the educational environment.

3.2.5. Evaluation

During the evaluation phase of the ADDIE methodology, the developed AR learning environment was evaluated from both educational and technological perspectives. A multidisciplinary panel of 50 professionals participated in the expert evaluation. The panel consisted of 10 science teachers, 10 biology teachers, 10 UX/UI specialists, 10 software engineers, and 10 educational technology specialists [49]. All experts were currently working in their respective professional fields and had a minimum of two years of professional experience.

The experts evaluated the proposed AR learning environment using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). This scale was used to standardize the experts' responses and facilitate the comparison of their perceptions regarding the proposed system. The five-point Likert scale is presented in Table 3.

The evaluation instrument consisted of four questions addressing four dimensions: usability, interactivity, learning effectiveness, and motivation and satisfaction. Usability assesses whether users can interact with and understand the application from their first use. Interactivity evaluates the quality and dynamism of the interaction with the three-dimensional anatomical models. Learning effectiveness assesses whether the AR

environment facilitates the understanding of human anatomy. Finally, motivation and satisfaction evaluate the extent to which the application increases students' interest and willingness to participate in the learning process. The four evaluation dimensions and their corresponding questions are presented in Table 4.

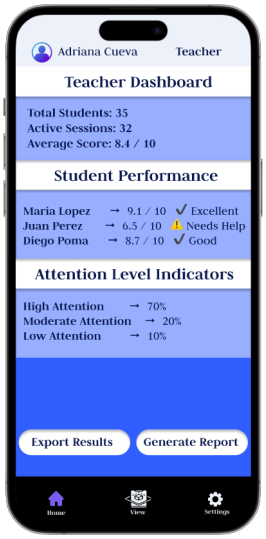


Figure 10. Teacher analytics dashboard for monitoring student performance and classroom engagement

Table 3. Five-point Likert scale for expert evaluation

Scale	Frequency description
1	Strongly disagree
2	Disagree
3	Neutral
4	Agree
5	Strongly agree

Table 4. Expert evaluation dimensions and assessment questions

Evaluation dimension	Assessment question
Usability	Is the AR mobile application easy to use and understand from the first use?
Interactivity	Does the system allow clear and dynamic interaction with the three-dimensional models of the human body?
Learning effectiveness	Did the use of AR facilitate the understanding of human body topics?
Motivation and satisfaction	Did the use of the application increase your interest and motivation to learn about the human body?

3.3. Statistical analysis

Descriptive and inferential statistical analyses were conducted to evaluate changes in students' learning performance and perceptions of the AR learning environment. Means and standard deviations were calculated for the pre-test and post-test scores and for the four evaluation dimensions: usability, interactivity, learning effectiveness, and motivation and satisfaction.

Paired-samples t-tests were used to compare pre-test and post-test scores within each group, while Welch's t-test was used to compare the improvement scores between the control and experimental groups. Statistical significance was established at $p < 0.05$. Cohen's d was calculated to quantify the magnitude of the observed differences and was reported alongside the corresponding p-values.

4. RESULTS

This section presents the conclusions drawn from the implementation and evaluation of the AR-based learning system. The results include an analysis of students' academic performance, a statistical evaluation, user feedback, expert assessments, and learning analytics data collected throughout the intervention process.

4.1. Pre-test and post-test results

A comparative analysis of the pre- and post-intervention assessments was conducted to evaluate changes in students' learning performance. As shown in Table 5, both groups improved their scores after the intervention. The control group increased from a mean pre-test score of 11.80 ± 2.46 to a post-test score of 14.20 ± 2.27, representing an improvement of 2.40 points. In comparison, the experimental group increased from 11.60 ± 2.02 to 18.11 ± 1.43, representing an improvement of 6.51 points.

The experimental group therefore showed a greater improvement in learning performance following the use of the AR learning environment. The between-group comparison of improvement was statistically significant ($p < 0.001$), with a large effect size (Cohen's $d = 1.41$).

Table 5. Pre-test and post-test learning outcomes by study group, showing the improvement associated with the AR-supported learning environment

Group	n	Pre-test	Post-test	Improvement	Cohen's d
Control	35	11.80 ± 2.46	14.20 ± 2.27	+2.40	0.71
Experimental	35	11.60 ± 2.02	18.11 ± 1.43	+6.51	2.78

4.2. Statistical analysis

Descriptive statistics were used to summarize students' learning performance and participants' perceptions of the AR learning environment. Mean values and standard deviations were calculated for the pre-test and post-test scores and for the four evaluation dimensions: usability, interactivity, learning effectiveness, and motivation. The results showed a greater improvement in the experimental group, with a mean increase of 6.51 points compared with 2.40 points in the control group. The between-group comparison indicated a statistically significant difference ($p < 0.001$), with a large effect size (Cohen's $d = 1.41$). Regarding the evaluation dimensions, motivation obtained the highest mean score (4.8 ± 0.2), followed by interactivity (4.7 ± 0.3), learning effectiveness (4.6 ± 0.4), and usability (4.5 ± 0.4), as shown in Table 6.

Table 6. Students' perceptions of the AR learning environment across the main evaluation dimensions

Variable	Mean	Standard deviation
Usability	4.5	0.4
Interactivity	4.7	0.3
Learning wffectiveness	4.6	0.4
Motivation	4.8	0.2

4.3. User reviews

This section presents the results of the evaluation conducted by the system's users. The study included 70 participants, who were surveyed using the rating scale defined in Table 3 and the questions listed in Table 4. This procedure allowed us to collect structured information on the participants' perceptions regarding the various aspects of the AR system that were evaluated.

Figure 11 presents the results of the survey conducted among 70 users, which reveal a predominantly positive trend in the evaluation of the AR system. Regarding usability, most participants fell into the "agree" and "strongly agree" categories, suggesting that the application is perceived as accessible and easy to understand from the very first interaction. Similarly, the interactivity pillar shows a high concentration of responses at the higher levels of the scale, reflecting a favorable perception of the manipulation of three-dimensional models. Regarding learning effectiveness, the distribution clearly leans toward positive evaluations, indicating that users recognize the tool's contribution to content comprehension. Furthermore, the motivation and satisfaction pillar achieves the highest scores, with a clear predominance of the "strongly agree" level, highlighting a significant impact on students' interest in learning. Overall, these results suggest that the system not only meets functional requirements but also enhances the educational experience from a pedagogical perspective.

4.4. Expert review

This section presents the results of the evaluation conducted by a group of experts comprising five professional profiles: 10 science teachers, 10 biology teachers, 10 user experience/user interface (UX/UI) specialists, 10 software engineers, and 10 educational technology specialists. All participants completed surveys designed to evaluate different aspects of the AR system. The inclusion of these profiles provided a comprehensive perspective, integrating pedagogical, technical, and UX viewpoints. Based on their responses, the data were

analyzed to identify the system's strengths, potential limitations, and overall level of acceptance in an educational context.

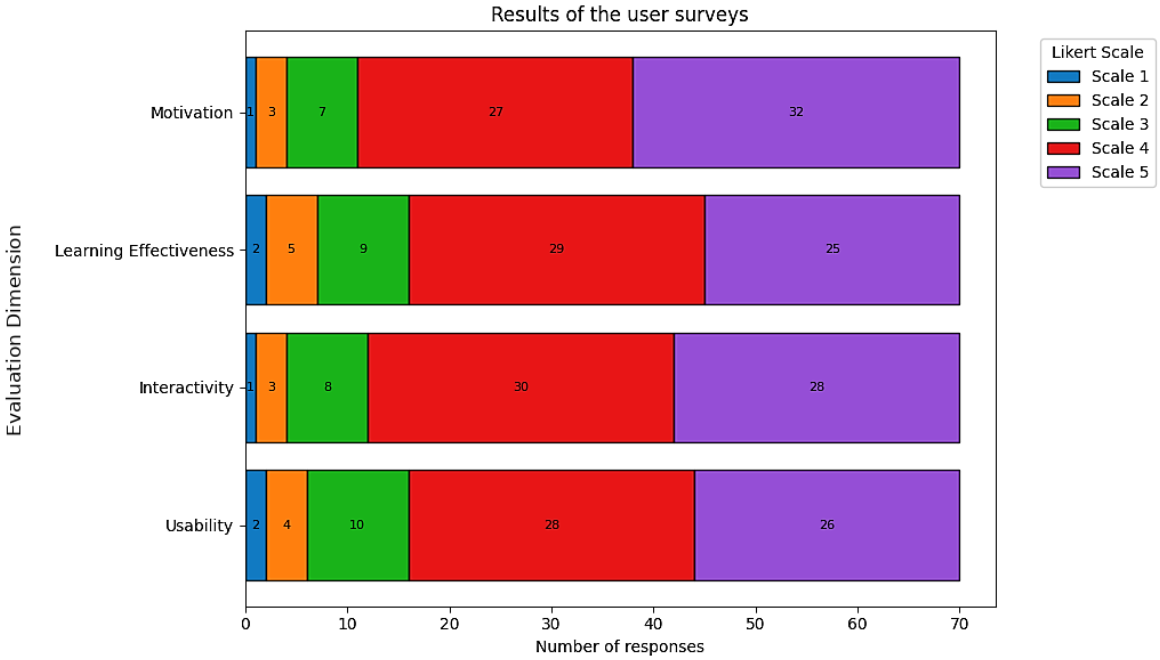


Figure 11. Students' perceptions of the AR learning environment across usability, interactivity, learning effectiveness, and motivation, highlighting its perceived contribution to engagement and anatomy learning

Figure 12 presents the results of the expert evaluation, which reflect the assessments made by the multidisciplinary panel. Overall, the distribution of responses shows a clear trend toward the higher levels of the Likert scale, indicating a favorable perception of the AR system across the various evaluation pillars. Regarding usability, the responses are more scattered compared to other dimensions, with a moderate presence at neutral and lower agreement levels, suggesting that, from a technical and design perspective, there is still room for improvement. Regarding interactivity, most experts rated the system positively, highlighting its ability to facilitate dynamic interaction with three-dimensional models. Regarding learning effectiveness, responses are concentrated at the "agree" and "strongly agree" levels, indicating that experts recognize the tool's pedagogical value in facilitating content comprehension. Finally, the motivation dimension also shows a strong positive trend, albeit with slightly greater variation, reflecting differences in the perception of interaction among different professional profiles. Overall, these results suggest that the system has been well received by experts, particularly for its educational value, while also highlighting specific areas—such as usability—that could benefit from further optimization.

4.5. Learning analytics results

The AR application included a learning analytics module designed to continuously monitor student interaction and learning progress throughout the intervention period. The metrics collected included quiz accuracy, engagement levels, completed activities, and frequency of interaction with the 3D anatomical models. As shown in Figure 13, both student engagement and quiz accuracy increased progressively over the nine-month intervention period. During the initial stages, students showed moderate levels of engagement as they adapted to the AR environment. However, continued interaction with the application led to greater engagement, improved performance on quizzes, and greater consistency in learning activities over time. The observed progression suggests that repeated exposure to the AR learning environment positively contributed to student motivation, active participation, and conceptual understanding of anatomical structures. Furthermore, the integration of learning analytics provided instructors with valuable insights into classroom performance and student progress, facilitating more informed pedagogical decision-making throughout the educational process.

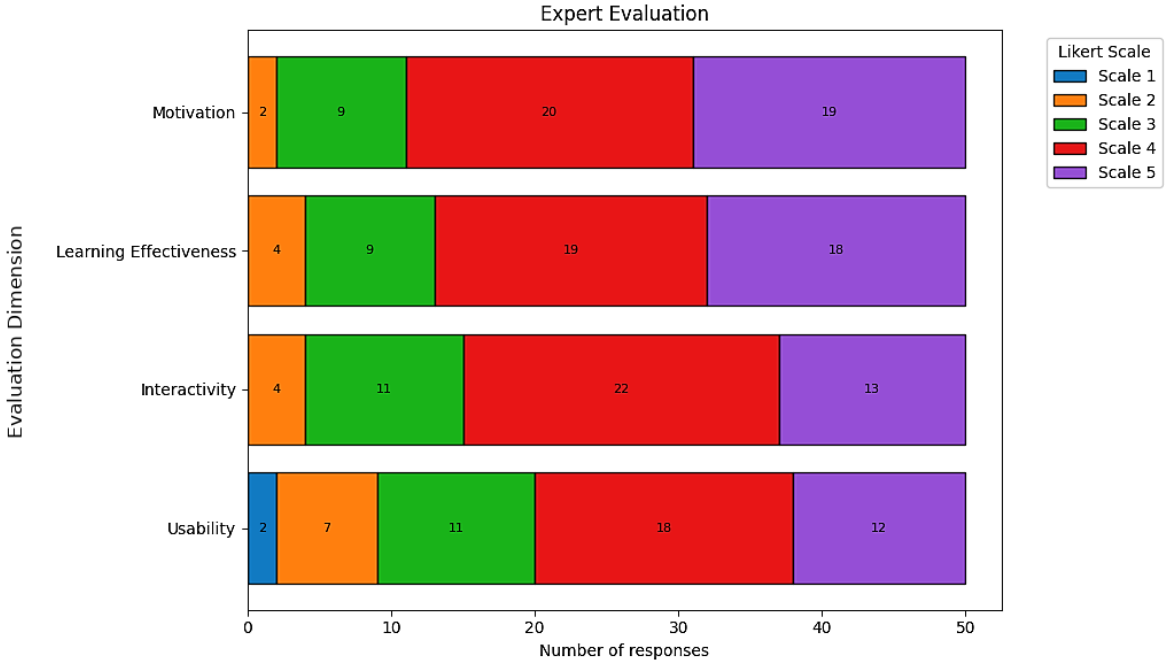


Figure 12. Expert evaluation of the AR learning environment across usability, interactivity, learning effectiveness, and motivation and satisfaction

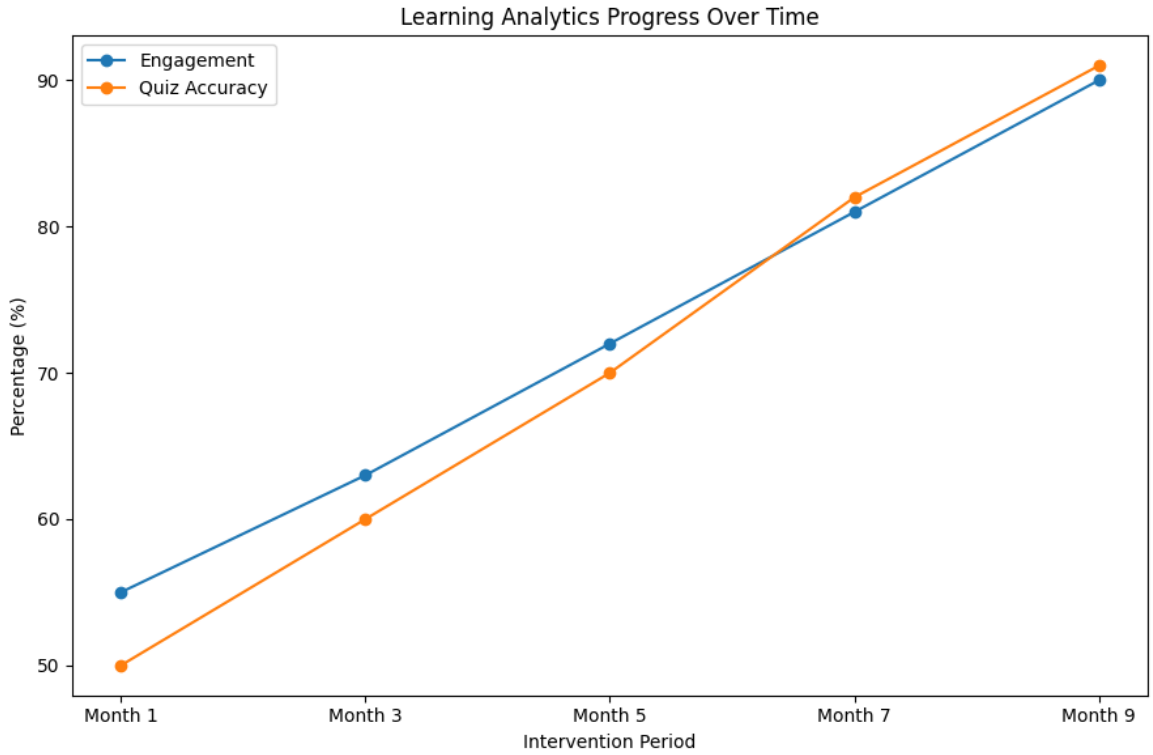


Figure 13. Progression of student engagement and quiz accuracy during the nine-month intervention, illustrating changes in participation and learning performance over time

5. DISCUSSION

The results indicate that the proposed AR learning environment was associated with greater improvement in anatomy learning in the experimental group than in the control group. The experimental group increased its mean score by 6.51 points, compared with 2.40 points in the control group, with a statistically significant between-group difference and a large effect size. This finding suggests that the use of AR provided additional learning support beyond conventional instruction.

One possible explanation for this improvement is the use of interactive three-dimensional visualization. Human anatomy involves spatial relationships between organs and body systems that can be difficult for elementary school students to understand through two-dimensional illustrations or verbal explanations alone. In the proposed environment, students could visualize and manipulate anatomical structures directly, allowing them to examine different perspectives and relationships between components of the human body. This interaction may have reduced the abstraction of anatomical concepts and facilitated the construction of more concrete mental representations. Similar benefits of AR-based visualization have been reported in educational studies involving complex scientific concepts [35], [36].

The positive results observed for motivation and interactivity can also be related to the active role provided by the AR environment. Instead of receiving information passively, students interacted with the learning content by exploring three-dimensional models and completing interactive activities. This combination of visual exploration and direct manipulation may have increased attention and participation during learning sessions. Previous AR studies have similarly reported increased engagement and interest when students interact directly with immersive educational content [29], [31], [34].

Interactive assessments and immediate feedback provided an additional mechanism supporting learning. The quizzes allowed students to apply the concepts presented through the AR models and receive immediate information about their performance. This connection between visualization, interaction, and assessment may have reinforced the learning process by allowing students to identify their progress during the activities. The favorable evaluations of learning effectiveness and motivation reported by students and experts are consistent with this integrated approach.

The learning analytics component further complemented the intervention by providing continuous information about student engagement and quiz performance throughout the nine-month period. Unlike a single pre-test and post-test comparison, the analytics provided longitudinal information about changes occurring during the learning process. The progressive increase observed in engagement and quiz performance suggests that repeated interaction with the AR environment was accompanied by sustained participation over time. This longitudinal component represents an important contribution because it combines immersive learning with continuous monitoring rather than evaluating the AR experience only at the end of a short intervention.

The nine-month intervention also provides a broader perspective than studies based on short-term AR implementations. While previous studies have demonstrated positive effects of AR on engagement and conceptual understanding during relatively brief interventions [29], [31], [34], the sustained duration of the present study allowed student engagement and quiz performance to be observed across an extended learning period. This longitudinal perspective provides additional evidence regarding the feasibility of maintaining AR-supported learning over time. Moreover, the integration of learning analytics differentiates the proposed environment from AR applications evaluated only through pre-test and post-test measures, as it provides continuous information about student participation and performance during the intervention. Therefore, the contribution of this study lies not only in the use of AR for anatomy visualization, but also in combining immersive learning, interactive assessment, and longitudinal learning monitoring within a single educational environment.

Overall, the findings suggest that the educational value of the proposed system does not depend solely on the use of AR technology, but on the integration of three-dimensional visualization, interactive activities, assessment, immediate feedback, and learning monitoring. This combination directly addresses some of the challenges associated with teaching anatomy to young learners by making abstract structures more visually accessible and providing opportunities for active exploration and continuous assessment.

5.1. Limitations

Despite the positive findings, several limitations should be considered when interpreting the results. First, the study involved a relatively small sample of 70 elementary school students, which may limit the generalizability of the findings to larger populations. Second, although the students were randomly selected

from the participating educational institution, the study employed a quasi-experimental design rather than a fully randomized controlled trial. Therefore, potential differences between the groups that were not captured by the measured variables cannot be completely excluded. Third, the intervention was conducted within a single educational institution and under a specific educational context, which may limit the transferability of the findings to schools with different characteristics, resources, or teaching practices. Finally, although the nine-month intervention provided longitudinal information on student engagement and learning performance, the study did not evaluate whether the observed learning gains were maintained after the intervention ended. These limitations should be considered when interpreting the results and provide opportunities for future research.

5.2. Future work

Future research should evaluate the proposed AR learning environment with larger student populations and across multiple educational institutions to determine whether the findings can be generalized to different educational contexts. Future studies could also integrate adaptive learning features that personalize activities, assessments, and feedback according to individual student performance and learning progress. In addition, the system could be evaluated in diverse educational settings with different teaching practices, technological resources, and student characteristics. Longer follow-up periods could also be considered to examine whether the learning improvements observed during the intervention are maintained over time.

6. CONCLUSION

This study developed and evaluated a mobile AR learning environment designed to support human anatomy education in elementary school. The main contribution of the study is the integration of interactive three-dimensional anatomical visualization, assessment activities, immediate feedback, and learning analytics within a sustained nine-month educational intervention. Rather than using AR solely as a visualization tool, the proposed environment combines immersive interaction with continuous monitoring of student learning progress.

The findings indicate that the AR-supported learning environment was associated with greater improvement in learning performance in the experimental group compared with the control group, together with favorable perceptions of usability, interactivity, learning effectiveness, and motivation and satisfaction. These findings suggest that AR can provide teachers with an additional instructional resource for presenting abstract anatomical concepts in a more visual, interactive, and engaging manner.

From a practical perspective, the proposed environment can support teachers by providing interactive anatomical resources and information about student progress that can complement conventional classroom instruction. The integration of learning analytics may also facilitate the identification of changes in student engagement and performance during the learning process, providing additional information that can support pedagogical decision-making.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data supporting the results of this study were generated by the authors during the course of their research. These data may be requested from Misael Lazo Amado and Laberiano Andrade-Arenas upon submission of a justified request.

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