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ORIGINAL MANUSCRIPT

The effects of augmented reality-supported instruction in tertiary-level medical education

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Abstract

A significant body of the literature has documented the potential of Augmented Reality (AR) in education, but little is known about the effects of AR-supported instruction in tertiary-level Medical Education (ME). This quasi-experimental study compares a traditional instructional approach with supplementary online lecture materials using digital handout notes with a control group ($n = 30$) and an educational AR application with an experimental group ($n = 30$) to investigate any possible added-value and gauge the impact of each approach on students' academic performance and training satisfaction. This study's findings indicate considerable differences in both academic performance and training satisfaction between the two groups. The participants in the experimental group performed significantly better than their counterparts, an outcome which is also reflected in their level of training satisfaction through interacting and viewing 3D multimedia content. This study contributes by providing guidelines on how an AR-supported intervention can be integrated into ME and provides empirical evidence on the benefits that such an approach can have on students' academic performance and knowledge acquisition.

KEYWORDS
augmented reality, human heart anatomy, medical education, mobile learning

Practitioner notes

What is already known about this topic

- Several studies have applied various Augmented Reality (AR) applications across different learning disciplines.
- The effects of AR on students' perceptions and achievements in higher education contexts is well-documented.
- Despite the increasing use of AR-instruction in Medical Education (ME), there has been no explicit focus on AR's effects on students' academic performance and satisfaction.

What this paper adds

- This quasi-experimental study compares the academic performance and training satisfaction of students in an experimental group (AR) and a control group (hand-out notes).
- This study provides instructional insights into, and recommendations that may help students achieve better academic performance in AR-supported ME courses.
- The experimental group reported greater training satisfaction than their counterparts.

Implications for practice and policy

- Students who followed the AR-supported instruction achieved better academic performance that those in the control group.
- AR-supported interventions encourage active learning and lead to significant performance improvement.
- The experimental group outperformed the control group in academic performance and training satisfaction measurements, despite the lower experimental group's lower pre-test performance scores.

INTRODUCTION

In tertiary-level Medical Education (ME) courses, students should understand the application of theoretical knowledge to the tasks and practices required to become medical practitioners. They also need to develop their knowledge from theory to practice, exploring learning tasks and developing practice-based clinical skills to support and improve knowledge acquisition (Moro et al., 2020; Scott et al., 2017). The widespread utilisation of digital learning materials, such as slideshow presentations, educational videos, and podcasts transforming any information gained by typical lectures into clear and meaningful content, is not always purposeful and understandable by ME students and practitioners, thus affecting their satisfaction and learning performance (Moro et al., 2017). Even the use of innovative learning technologies in well-controlled learning settings cannot always satisfy students' expectations in relation to performing better and practically applying knowledge gained through theory-based lectures. Consequently, students strive hard for success in practice-based tasks and become passive recipients of the instructor's guidance, significantly influencing their learning performance

(Pellas et al., 2019; Tang et al., 2020). Several constraints, like time-limited experiments, the lack of an instructor's presence when each student is undertaking a task, and the scarcity of technological infrastructure, can cause barriers to using well-known Information and Communication Technology (ICT) tools to their full capacity (Zargaran et al., 2020). Typical examples include medical and traumatic emergencies to which ME students need to respond effectively or unnatural tasks that require the implementation of high-cost training modalities (Couperus et al., 2020). Therefore, such practices are considered inappropriate and ineffective not only regarding the impact they have on students' performance but, most importantly, on their potential to support students in conceptualising and understanding the notions being taught.

Advancements in computing power, graphical realism, and fidelity in simulations offer significant possibilities in complex education and training contexts such as those encountered in ME, leading industry analysts to predict that ‘immersive’ technologies, such as Virtual Reality (VR) and Augmented Reality (AR) will be increasingly used. In the case of AR, the global market has been projected to grow at a 23% compound annual rate between 2017 and 2023 (Zweifach & Triola, 2019). AR is one of the most remarkable and promising technologies for medical training solutions as it allows interaction between a system interface with real and digital features/elements. AR comprises a set of computer-generated graphics overlaid on real world objects to highlight and/or enhance certain features, most commonly using handheld computing devices like smartphones, or AR glasses (Pellas et al., 2019).

To overcome the drawbacks and barriers of utilising theoretical knowledge in ME training settings, studies have identified the following advantages of using AR-supported instruction (Barsom et al., 2016; Couperus et al., 2020; Moro et al., 2020): (a) it decreases the technological equipment needed to eliminate human faults, which could be irreversible for patients; (b) it increases the scalability of any medical learning content, using several human senses (visual, auditory, haptic); and (c) it enhances learning by providing immediate feedback in real-time with embodied motions (for example, graphic animations). Further, AR-supported instruction can support students to become more productive by creating more meaningful navigation paths/interaction with the system when exploring the learning material (Kiourexidou et al., 2015).

There is a broad agreement across researchers that AR-supported instruction can generally promote active learning and assist students to explore freely any cognitively demanding tasks using simulated, realistic settings with representational fidelity, thus developing students' theoretical knowledge through instructional practices using portable and handheld devices (Tang et al., 2020). Studies have addressed the value of different AR applications in relation to student experience tasks or practices in ME in a number of ways, including: assessing students' learning efficiency by visualising the data with the infographic illustration of AR apps (Dehghani et al., 2020); exploring the feasibility of a three-dimensional (3D) human heart module (Kiourexidou et al., 2015); and comparing different computing devices to assess whether learning structural anatomy by utilising VR or AR-supported technology can be as effective as tablet-based applications (Moro et al., 2017). Other research (Moro et al., 2020; Vergel et al., 2020) has focused explicitly on the comparison and identification of the most appropriate combination of immersive technology solutions (HoloLens, VR-tabletop) for the didactic of anatomy training.

Despite the growing interest in using AR, little is known about whether this technology has an impact on students' academic performance and training satisfaction in ME. In the context of this study, we address these issues by comparing the effects on learners of using AR-supported activities to those of using the widely adopted digital handout notes in ME courses. Both approaches were utilised supplementarily to the mainstream method (the lecture).

BACKGROUND

ICT-supported instruction in ME

Educators and instructors face significant challenges within technology-supported contexts in ME, ranging from how to assist students to continue studying and practicing their theoretical knowledge, to improving their performance with well-designed instructional practices. To engage and motivate students to study and learn, instructors and educators need to identify ICT-supported tasks which will have a more positive impact on their motivation and performance than conventional lectures. Examples include studies (AlNassar et al., 2012; Zargaran et al., 2020) which have assessed the use of educational videos in ME and found that students seemed to perform significantly better than those who followed the traditional methods. Scott et al. (2017) also showed that the use of mobile devices in clinical practices assisted students to gain new knowledge; and AlNassar et al. (2012) reported that familiar ICT tools, web-based resources, and videos allow students to assess and receive feedback on their experience and/or perceptions. These studies suggest that ICT tools allow students to cultivate a range of cognitive and practical skills in safe and well-controlled learning settings.

However, several concerns have also been raised by these studies, including: (a) the time taken to record the videos and the ethics of recording live patients (Zargaran et al., 2020); (b) the lack of transparency and misperceptions that can occur when using mobile devices, as well as concerns related to ethics related to students, physicians and patients (Scott et al., 2017); and (c) the lack of interest show by students in learning while watching a video presentation as the element of interactivity is missing, rendering them passive receivers of information (Al Nassar et al., 2012). The main criticism of these uses of ICT is that they did not emphasise the structure required to support or improve student performance—structure that would assist them to cultivate their cognitive thinking skills and lead to deeper understanding and expertise in similar, real-life situations.

AR-supported simulations in ME

Using AR-supported simulation in applications to teach and learn fundamental medical concepts relies on merging physical (‘target tracking’) with digital features and objects. There are several modes of communication and interaction between system and user with ‘smart’ computing devices, such as smartphones or tablets, including feedback, with visual and/or acoustic cues, and user input methods, using gesture recognition, the direction of gaze, facial expressions and/or speech (Barsom et al., 2016). An AR-supported learning experience in ME can be improved when it is used via interactive tasks with access to virtual learning content. To this end, students have the chance to explore their perspective and control—with hands-on tasks—the virtual content, to monitor the learning process by utilising real-time information with high representational fidelity, receive real-time feedback, and keep-in-touch with other colleagues during the learning tasks at the same time (Moro et al., 2017; Vergel et al., 2020). For instance, students can display the virtual educational content by simply pointing a camera at relevant real-world objects in their environment inside or outside the classroom (Moro et al., 2020). AR applications are displayed as ‘pop-up’, visually appealing simulations or interactive animations rendered via a wide variety of tracking methods (physical objects, ‘Quick Response’ codes; Pellas et al., 2019).

Several different medical disciplines have conducted studies to evaluate the efficacy of AR-supported simulation training. Particularly, Kiourexidou et al. (2015) evaluated the usability and feasibility of an AR application dedicated to human heart anatomy education.

The main results suggested the appropriateness of AR technology in anatomy education especially regarding the deconstruction of abstract concepts that needed to be studied in the laboratory. Moro et al. (2017) investigated whether learning structural anatomy utilising VR or AR is as effective as using tablet applications to enhance student learning, engagement, and performance. The use of 'immersive' technologies was not only found to be as valuable for teaching anatomy as tablet devices but also promoted intrinsic benefits, such as increased student immersion and engagement. Moro et al. (2020) delivered a comparative study of AR-supported instruction using the Microsoft HoloLens versus a mobile handheld tablet device. The results indicated that students using the HoloLens had slight dizziness which, however, did not have a significant impact on the learning process or their perceptions regarding the potential of such an 'immersive' technology. Vergel et al. (2020) assessed student experience with an optical-based AR setup implemented with a Microsoft HoloLens device and a semi-immersive setup based on a VR Table. The latter was the optimal alternative to anatomy training owing to its user-friendly nature, in terms of ergonomics and interaction, as well as the high degree of student-reported satisfaction. Dehghani et al. (2020) pointed out that the applicability of AR-supported instruction had significant effects on 10th-grade students learning biology. The combination of AR apps and infographic visualisation mitigated the complexity of difficult issues owing to the variety of visual objects which were projected.

The findings from these studies indicate that the use of mobile devices and AR-supported instruction in both undergraduate and graduate medical curriculum programs can lead to the development of a better understanding of fundamental medical science concepts and tasks. Students spend much more time investigating certain hypotheses via the 3D animations and visual elements afforded by AR which are difficult to be projected through regular discourse in the context of the lecture. Moreover, AR-supported instruction offers a more student-centred learning experience that is offered in contexts like laboratories or other more authentic learning contexts and increases student engagement for exploration and experimentation using mobile devices.

Despite these advantages, studies (Kiourexidou et al., 2015; Moro et al., 2017, 2020) have also highlighted drawbacks and challenges to the use of AR to support learning, including: (a) the hardware equipment, such as smartphones or tablets, to enable AR-supported 'marker-based' instruction; (b) usability and potential ergonomic issues with mobile computing devices; and (c) the need for appropriate user interface development, and data structures, to mitigate dizziness and fatigue issues that may arise.

The literature demonstrates the increasing interest in evaluating the appropriateness of AR in medical training. However, early findings are limited and insufficient to recommend its adoption into ME programs. Relevant studies (Kiourexidou et al., 2015; Moro et al., 2017) have concluded that students' preferences and attitudes do not provide satisfactory evidence on which practitioners may draw in delivering AR-supported instruction in medical courses, implying the need for additional empirical research (Dehghani et al., 2020; Vergel et al., 2020) into the effect of AR-supported instruction on ME students' academic performance and satisfaction.

This study therefore investigates whether AR-instruction can have a positive impact on learning effectiveness in medical training and on training satisfaction, by incorporating such practice into (online) ME courses.

The research questions (*RQs*) that the study aims to investigate are:

RQ1. Is there any significant difference between the academic performance of students who followed AR-supported instruction and their counterparts who received handout notes?

RQ2. Is there any significant difference between the training satisfaction of students who followed AR-supported instruction and their counterparts who received handout notes?

METHOD

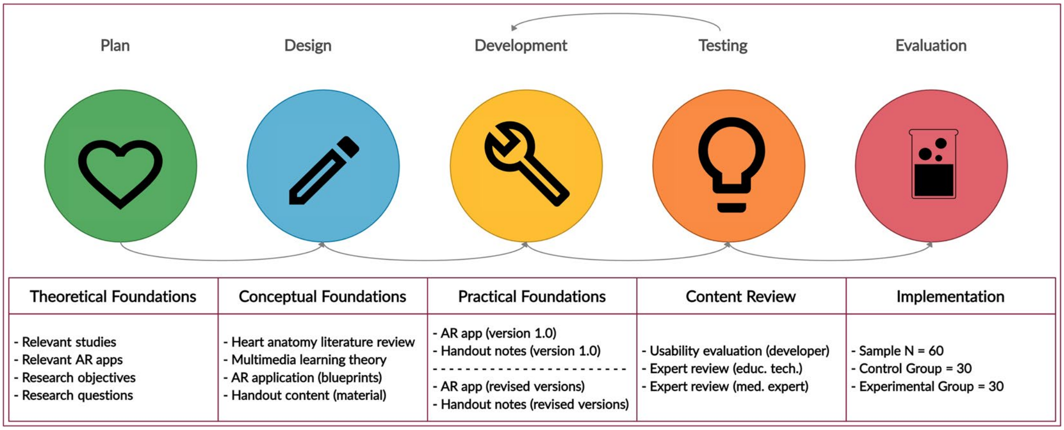
Research context

We conducted a quasi-experimental study with students emerging from a public tertiary education institution in Greece. The selected course, about ‘human anatomy’, was delivered supplementarily online (in addition to traditional lectures) and the subject under investigation was the ‘anatomy of heart’. The aim was to foster students' knowledge of the various components of the heart by enabling students to explore its operations and observe its functions. Figure 1 provides an overview of the activities that formed the research design.

The study followed the non-equivalent control-treatment group design with pre-test/post-test measurements (Cohen et al., 2007). The non-randomised sample approach enabled us to have the same sample size in both groups and an almost equal variation in terms of the participants' gender to prevent undetected constant bias and flawed inference in this study's results (Shadish et al., 2002). To rule out the novelty effect, students who expressed an interest in participating in this study were asked to complete a demographic information survey, prior to taking part, to elicit their experience of using digital learning resources (eg, Learning Management Systems, digital textbooks) as well as mobile devices (eg, tablets, smartphones) for self-directed learning (eg, course podcasts, lecture webcasts) or other course-related activities (eg, note taking, presentations). This enabled us to prevent any ‘digital inequality’ across the participants, ensuring that all of them had access to either the AR app (Experimental Group—EG) or the handout notes (for the Control Group—CG) during their learning tasks (Cruz-Jesus et al., 2015).

Participants

The target population was first-to-third-year students (convenience sampling approach) divided equally in two groups: the EG (males = 16, females = 14), which adopted the AR application; and the CG (males = 17, females = 13), which adopted the handout notes.



Theoretical Foundations	Conceptual Foundations	Practical Foundations	Content Review	Implementation
- Relevant studies - Relevant AR apps - Research objectives - Research questions	- Heart anatomy literature review - Multimedia learning theory - AR application (blueprints) - Handout content (material)	- AR app (version 1.0) - Handout notes (version 1.0) - AR app (revised versions) - Handout notes (revised versions)	- Usability evaluation (developer) - Expert review (educ. tech.) - Expert review (med. expert)	- Sample N = 60 - Control Group = 30 - Experimental Group = 30

FIGURE 1 Research design

Instrumentation

To measure students' academic performance across the attained learning objectives, a quiz consisting of 21 items and 12 open-ended questions was prepared. The evaluation content of the pre-and post-test was the same, but the order of the items was changed to avoid the same-set response effect.

In addition, a questionnaire related to learning satisfaction was adopted and adjusted to the needs of this study (Wei & Chou, 2020). The utilised instrument consists of 10 items (S1–S10) distributed across three constructs: (C1) 'Learner Control' (α = 0.71); (C2) 'Motivation for Learning' (α = 0.79); and (C3) 'Self-directed Learning' (α = 0.82).

The participants' answers were given on a 5-point Likert scale (1: 'Strongly Disagree' to 5: 'Strongly Agree'). The data collection was performed anonymously and with participants' informed consent.

Procedure

For the use by the EG, a mobile AR application (app) named *HeARt* was developed. The design decisions related to the elements of the app (functional, non-functional, technical requirements) and its content (high/low fidelity frames) were driven by the relevant ME literature and the principles of the Multimedia Learning Theory (MLT) as Table 1 details (Mayer, 2009).

A prototype was developed using Unity 3D (to set up the heart scenes), Microsoft Visual Studio (to implement the app's functionalities), and the Vuforia engine (to create the interactive AR features). The blueprints of the app (Figure 2) and the prototype's intermediate versions went through rigorous reviews performed by experts in the fields of ME and instructional design.

Different 3D visual representations and animations were employed to allow students diverse ways of interacting (fixed-point/inverse iteration, bisection, scaling) through which to develop a deeper understanding of the app's various operations (Figure 3).

In line with the primary goal of this study, a 'help' button was created, allowing access to instructions related to the augmentation steps and the interaction techniques (Figure 4). It was expected that the help system would reduce user errors and eliminate the impact of students' unfamiliarity with this technology.

For the CG, the handout notes (Figure 5) were naturally more restrictive as far as the opportunities for interaction were concerned. Nevertheless, different forms of visual representation were included to increase engagement and textual information was kept to a minimum to reduce cognitive load.

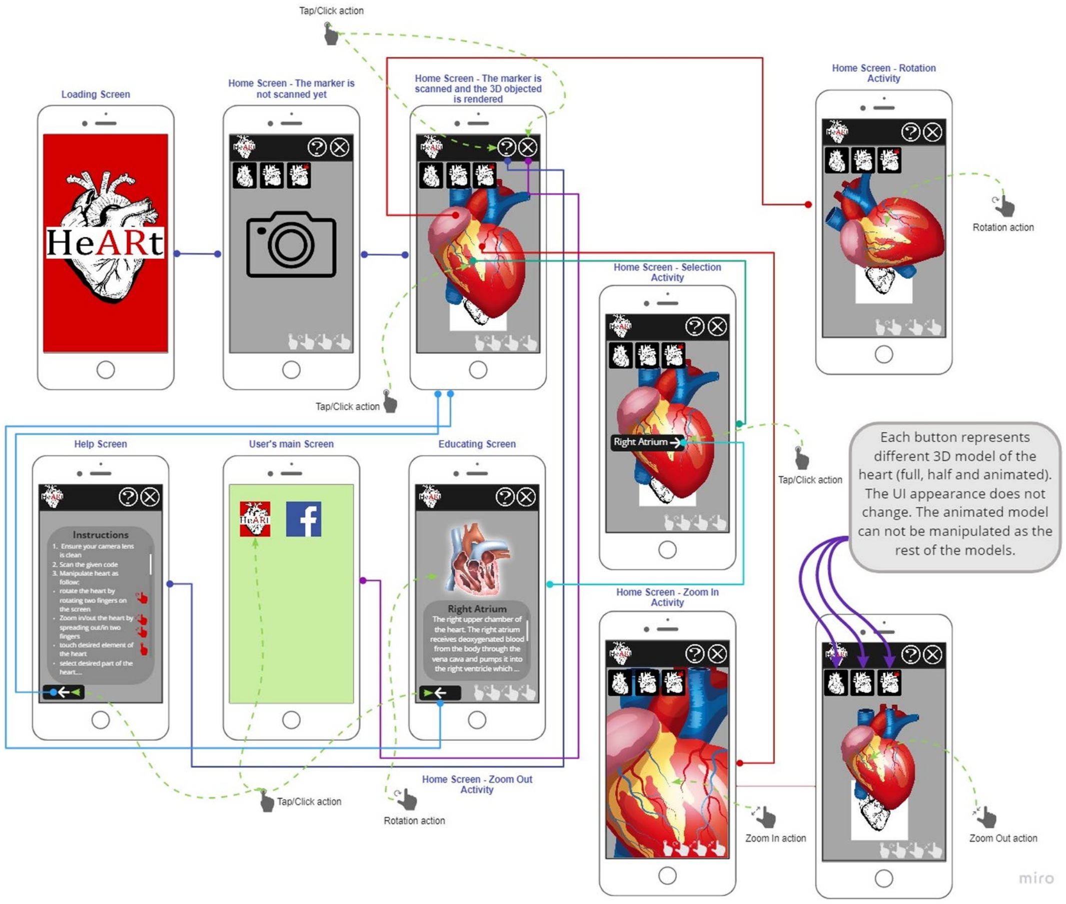
Experimental setup

The study was conducted over the course of four weeks with the experiment occurring in the context of a supplementary (online) workshop conducted via 'Zoom' meeting platform during the COVID-19 outbreak. To explore the change in students' performance and degree of training satisfaction, we adopted a quantitative approach.

To evaluate participants' knowledge before the conduct of the intervention and gauge the difference in acquired knowledge after its completion, a custom knowledge quiz was designed. The quiz comprised three sections, covering topics related to terminology, anatomy, and functions. The quiz items were prepared in line with formal evaluation methods used in this scientific discipline (True/False, labelling, and multiple-choice questions). Each correct

TABLE 1 Application of the multimedia learning theory principles to the design of the *HeARt* app

No	Principles of MLT	Incorporation into the AR application
Principles that minimise extraneous load		
1	*Coherence principle*: Exclusion of extraneous materials, objects, and variables (p. 89)	• Incorporation of 3D models/illustrations with high fidelity. • Minimalistic user interface design. • No use of unessential sounds. • No cluttered structure for the learning content.
2	*Signaling principle*: Highlight the cues for organising better the fundamental embedded materials. (p. 108)	• Only one 3D model could be selected at a time. • Only one component of the rendered 3D model could be manipulated. • Selected components are highlighted and accompanied by one label only. • The user interface button corresponding to the selected 3D model remains highlighted until another 3D model is selected. • Integration of help button detailing how to interact with the application. • Integration of static images with pseudo-movement illustrations explaining the interactivity functions.
3	*Redundancy principle*: Provide visual images and narration rather than images or hardcopies text. (p. 118)	• The 3D models illustrated only the essential structures. • The 'home' screen displays only naming labels. • The 'educational view' displays text-based information related to the selected structure of the 3D model only.
4	*Spatial contiguity principle*: Close presentation of the included text and images on user's screen (p. 135).	• Terminology labels appear next to the selected structure of the 3D model. • The educational text appears strictly under the 3D virtual model. • Integration of the same style font in every view of the application.
5	*Temporal contiguity principle*: Simultaneous integration of text and graphic rather than successively. (p. 153)	• Animation clips synchronised in a timeline. • Animation clips set to continuous lopping. • The educational text is always visible.
Principles that manage intrinsic load		
6	*Segmenting principle*: Presentation of multimedia messages in student-centred controlled segments than continuously. (p. 175)	• Integration of non-linear navigation style (lack of predefined paths). • The 3D models and the respective structures can be selected at any order. • No timeout restrictions were applied.
7	*Pre-training principle*: Identification of the names and characteristics of the main concept can lead to a deeper understanding. (p. 189)	• An orientation session was offered related to the functionalities of the AR app. • An instructional video was offered related to the functionalities of the AR app. • An introductory session was offered related to the learning objectives and the respective exercises.
Principles that optimise germane load		
8	*Multimedia principle*: Combining images with text allows users to understand better the learning materials (p. 223).	• Each structure of the 3D models is associated to the respective terminology and description. • The embedded animations include descriptive text.
9	*Image principle*: Avoidance of screening the speaker's photo into the screen. (p. 242)	• Pictures/avatars of real/virtual teachers have not been integrated in the application.



Instructions
1. Ensure your camera lens is clean
2. Scan the given code
3. Manipulate heart as follow:
- rotate the heart by rotating two fingers on the screen
- Zoom in/out the heart by spreading out/in two fingers
- touch desired element of the heart
- select desired part of the heart....

Right Atrium
The right upper chamber of the heart. The right atrium receives deoxygenated blood from the body through the vena cava and pumps it into the right ventricle which ...

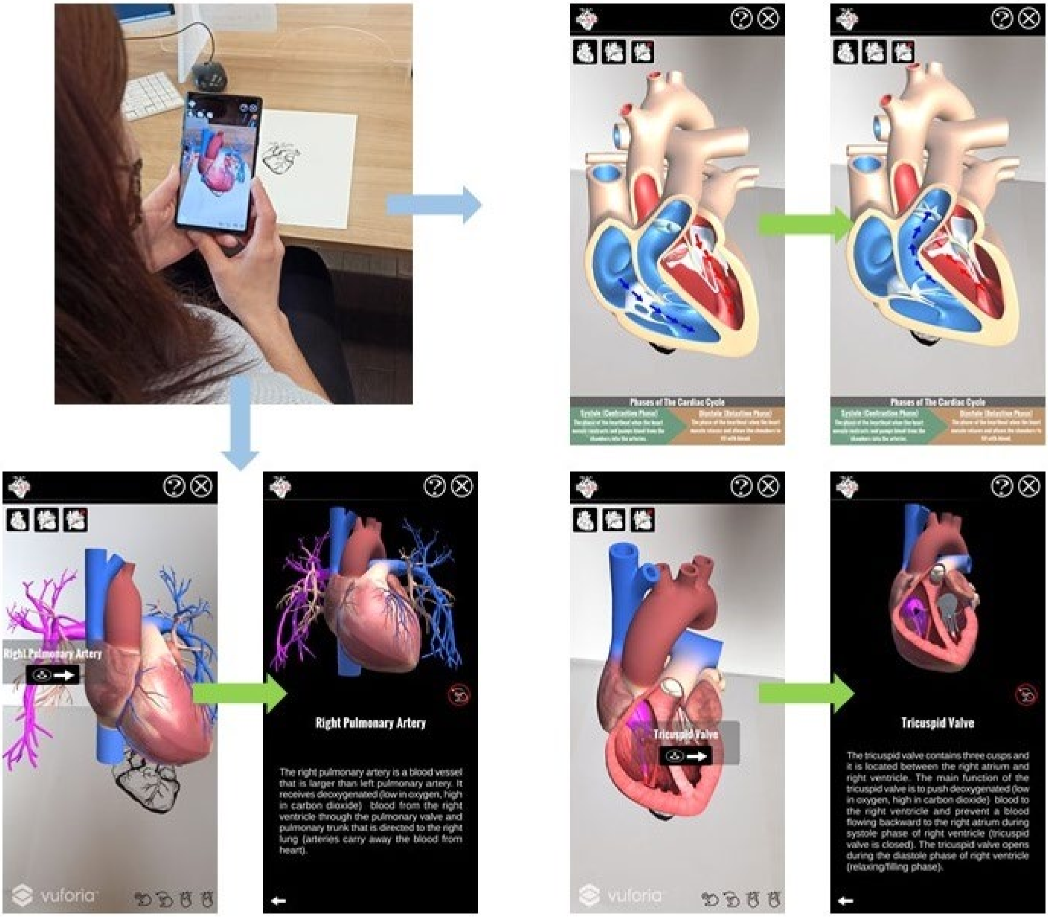
Each button represents different 3D model of the heart (full, half and animated). The UI appearance does not change. The animated model can not be manipulated as the rest of the models.

FIGURE 2 The design procedure

answer was given a score of 1 (maximum score = 33); no negative marking was imposed (ie, there was no penalty for answering incorrectly). Nevertheless, students were encouraged to carefully read and attempt to answer every question to the best of their ability. Table 2 provides an overview of the experiment design.

Before the experimental activity, a presentation related to different innovative technologies (eg, interactive books/videos, VR/AR) in ME education was delivered to all participants; this was communicated as being compensation for students giving their time to participate in the study. Accordingly, a brief summary-lecture related to human heart anatomy was delivered, again to all students, by the ME expert. The EG students received an additional session covering the following topics: (a) Introduction to AR technology; (b) The potential of AR in (medical) education; and (c) Orientation to the provided ME AR app (Figure 6). At the end of the experiment, each student cohort was granted access to the alternative didactic approach so that all students could explore alternative learning methods.

Participants were then encouraged to study the learning material, based on the provided supplementary approach (AR app or handouts), for as long as it took for them to feel confident in their acquired/revised knowledge. In general, students spent 40–50 minutes studying the handouts' material/interacting with the AR application, including spontaneous questions and requests for clarifications which were addressed to the ME expert, during the e-learning session. To eliminate the impact of the Short-Term Memory effect (ie, requesting students



Right Pulmonary Artery

The right pulmonary artery is a blood vessel that is larger than left pulmonary artery. It receives deoxygenated (low in oxygen, high in carbon dioxide) blood from the right ventricle through the pulmonary valve and pulmonary trunk that is directed to the right lung (arteries carry away the blood from heart).

Tricuspid Valve

The tricuspid valve contains three cusps and it is located between the right atrium and right ventricle. The main function of the tricuspid valve is to push deoxygenated (low in oxygen, high in carbon dioxide) blood to the right ventricle and prevent a blood flowing backward to the right atrium during systole phase of right ventricle (tricuspid valve is closed). The tricuspid valve opens during the diastole phase of right ventricle (relaxing/filling phase).

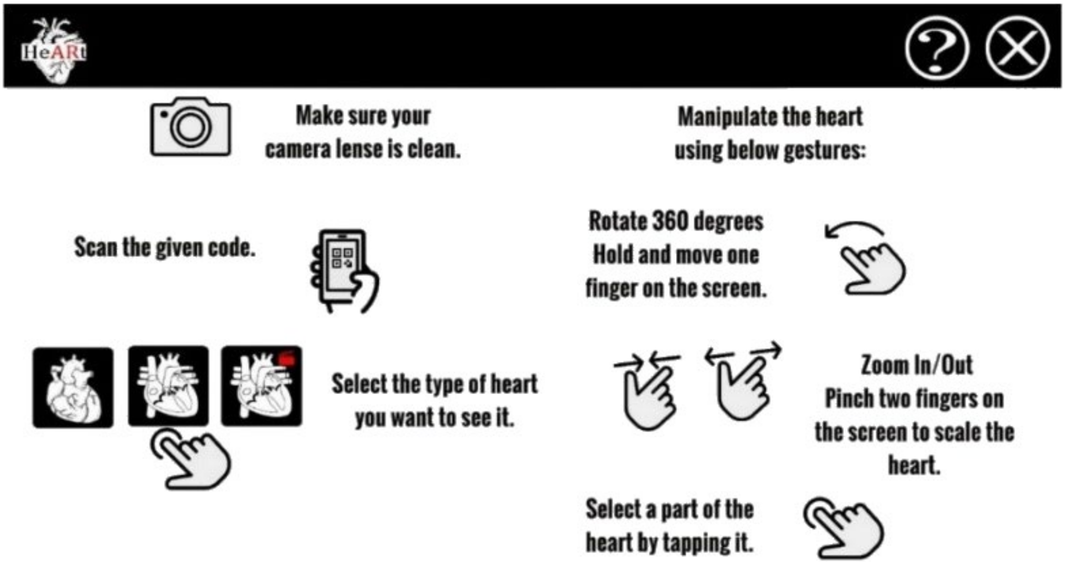
FIGURE 3 Overview of 3D models

to undertake the knowledge assessment quiz immediately after studying the educational material), the post-test was performed a week later. It should be noted that, no information was collected regarding students' self-learning approach (ie, interaction with the provided handouts/AR app outside the dedicated laboratory session) for practical reasons.

Prior to the post-test dissemination, EG participants were requested to uninstall the AR app and access to the handout forms (Google Drive) was restricted for CG participants. To avoid an advantage to the CG during the post-test evaluation process, the wording in the assessment forms was edited. The order of the questions (sections, questions, answers' order) was also altered. To prevent cheating during the evaluation process, participants were asked to switch on their cameras (where applicable) and the ‘no discussion rule’ was applied. The evaluation process was invigilated by the ME expert and a member from the research team. Upon completion of the post-test, the training satisfaction survey was distributed to both groups, marking the end of this study.

Data analysis

To identify any possible influence between the students' background information (demographics, ME year, English level) and their learning achievements, multiple correlation tests



Make sure your camera lense is clean.

Scan the given code.

Select the type of heart you want to see it.

Manipulate the heart using below gestures:

Rotate 360 degrees Hold and move one finger on the screen.

Zoom In/Out Pinch two fingers on the screen to scale the heart.

Select a part of the heart by tapping it.

FIGURE 4 Interaction techniques

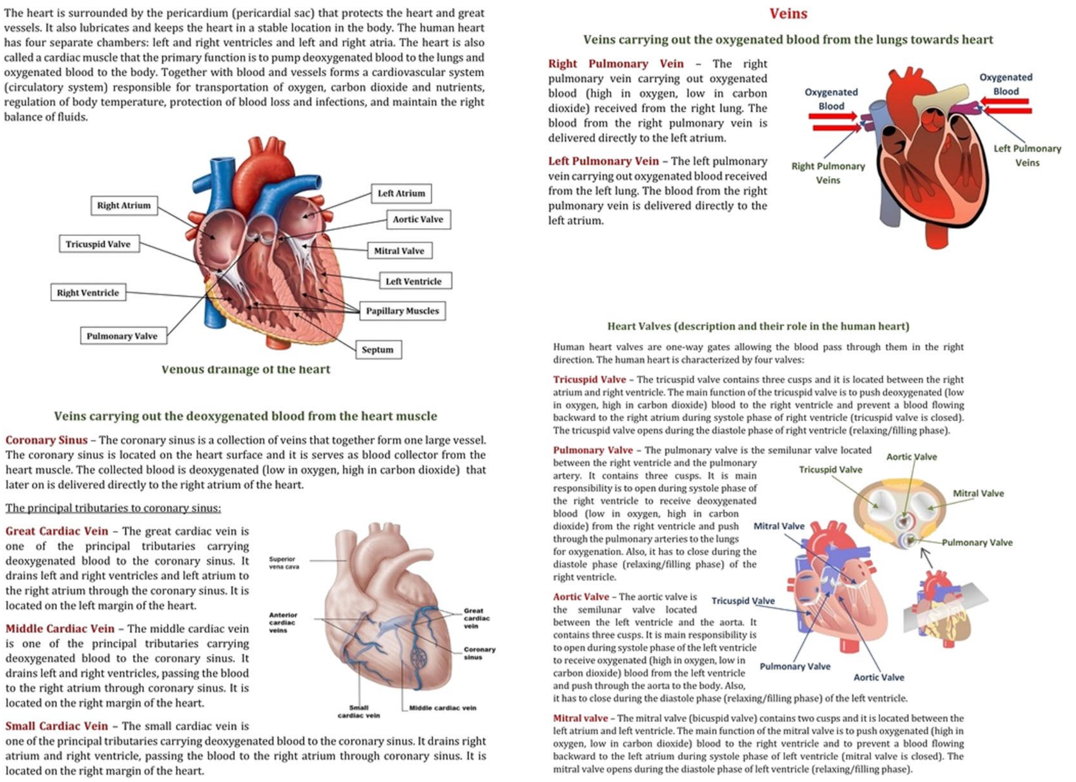
(Spearman's *rho*) were performed. Accordingly, the assessment data were analysed using descriptive statistics followed by *t*-tests to determine the pre-existing knowledge of the cohorts and the effect that each instructional approach had on their academic performance. For the questionnaire data, one-way MANOVA (Multivariate Analysis of Variance) was performed between the CG and the EG against the main instrument constructs (dependent variables). For the rejection of the null hypothesis, we assumed statistical significance for $p < 0.05$. All the statistical analyses were performed using the *R* software.

RESULTS

Demographics

Both groups had a similar gender balance, a relatively small variation in age group profile, and a moderate distribution in terms of study year (Table 3). Nevertheless, based on the claims made by Bleakley (2014) about the gender shift in ME (from male dominance to female dominance), it was deemed reasonable to explore the impact that participants' gender might have had on performance when correlated to the utilised instructional method. Based on the data plots, an observation was made indicating that female students may have benefited more from the AR approach. The correlation results were low and statistically insignificant. Another issue which could influence the validity of the experiment was students' English level as it may have impacted the development of their theoretical/conceptual understanding and, therefore, performance. On average, students from both groups reported ‘advanced’ competencies in English, so we assume that the language barrier was not a concern.

Finally, our discussions with the ME expert revealed that students tend to study anatomy almost exclusively from textbooks. This is attributed to the stability of the subject, especially when compared to other subdomains (cf. drug developments, medicine laws). Examining participants' frequency of use of digital learning resources was important as it could reveal information related to their familiarity, readiness, and willingness to use such tools. Students



The heart is surrounded by the pericardium (pericardial sac) that protects the heart and great vessels. It also lubricates and keeps the heart in a stable location in the body. The human heart has four separate chambers: left and right ventricles and left and right atria. The heart is also called a cardiac muscle that the primary function is to pump deoxygenated blood to the lungs and oxygenated blood to the body. Together with blood and vessels forms a cardiovascular system (circulatory system) responsible for transportation of oxygen, carbon dioxide and nutrients, regulation of body temperature, protection of blood loss and infections, and maintain the right balance of fluids.

Venous drainage of the heart

Veins carrying out the deoxygenated blood from the heart muscle

Coronary Sinus – The coronary sinus is a collection of veins that together form one large vessel. The coronary sinus is located on the heart surface and it is serves as blood collector from the heart muscle. The collected blood is deoxygenated (low in oxygen, high in carbon dioxide) that later on is delivered directly to the right atrium of the heart.

The principal tributaries to coronary sinus:

Great Cardiac Vein – The great cardiac vein is one of the principal tributaries carrying deoxygenated blood to the coronary sinus. It drains left and right ventricles and left atrium to the right atrium through the coronary sinus. It is located on the left margin of the heart.

Middle Cardiac Vein – The middle cardiac vein is one of the principal tributaries carrying deoxygenated blood to the coronary sinus. It drains left and right ventricles, passing the blood to the right atrium through coronary sinus. It is located on the right margin of the heart.

Small Cardiac Vein – The small cardiac vein is one of the principal tributaries carrying deoxygenated blood to the coronary sinus. It drains right atrium and right ventricle, passing the blood to the right atrium through coronary sinus. It is located on the right margin of the heart.

Veins

Veins carrying out the oxygenated blood from the lungs towards heart

Right Pulmonary Vein – The right pulmonary vein carrying out oxygenated blood (high in oxygen, low in carbon dioxide) received from the right lung. The blood from the right pulmonary vein is delivered directly to the left atrium.

Left Pulmonary Vein – The left pulmonary vein carrying out oxygenated blood received from the left lung. The blood from the right pulmonary vein is delivered directly to the left atrium.

Heart Valves (description and their role in the human heart)

Human heart valves are one-way gates allowing the blood pass through them in the right direction. The human heart is characterized by four valves:

Tricuspid Valve – The tricuspid valve contains three cusps and it is located between the right atrium and right ventricle. The main function of the tricuspid valve is to push deoxygenated (low in oxygen, high in carbon dioxide) blood to the right ventricle and prevent a blood flowing backward to the right atrium during systole phase of right ventricle (tricuspid valve is closed). The tricuspid valve opens during the diastole phase of right ventricle (relaxing/filling phase).

Pulmonary Valve – The pulmonary valve is the semilunar valve located between the right ventricle and the pulmonary artery. It contains three cusps. It is main responsibility is to open during systole phase of the right ventricle to receive deoxygenated blood (low in oxygen, high in carbon dioxide) from the right ventricle and push through the pulmonary arteries to the lungs for oxygenation. Also, it has to close during the diastole phase (relaxing/filling phase) of the right ventricle.

Aortic Valve – The aortic valve is the semilunar valve located between the left ventricle and the aorta. It contains three cusps. It is main responsibility is to open during systole phase of the left ventricle to receive oxygenated (high in oxygen, low in carbon dioxide) blood from the left ventricle and push through the aorta to the body. Also, it has to close during the diastole phase (relaxing/filling phase) of the left ventricle.

Mitral valve – The mitral valve (bicuspid valve) contains two cusps and it is located between the left atrium and left ventricle. The main function of the mitral valve is to push oxygenated (high in oxygen, low in carbon dioxide) blood to the right ventricle and to prevent a blood flowing backward to the left atrium during systole phase of left ventricle (mitral valve is closed). The mitral valve opens during the diastole phase of left ventricle (relaxing/filling phase).

FIGURE 5 Indicative sections of the handout material (drawings adopted from www.hiclipart.com)

from both groups claimed to have been using digital learning resources equally often (4–5 times/week), leading to the conclusion that digital literacy was not a concern.

Academic performance

The assessment forms were distributed electronically, and all participants completed them with no blank answers. The participants from both groups completed online the following: (a) a demographic survey; (b) a pre/post-study quiz related to participants' academic performance/learning outcomes; and (c) a questionnaire related to participants' training satisfaction. This process allowed us to: (a) validate the educational significance and appropriateness of the utilised instructional strategies; (b) gather data on the social validity of the study; and *(c)* assess whether the achieved learning outcomes were useful and relevant to the scope of this course (Cruz-Jesus et al., 2015).

Cronbach's α (internal consistency) for the pre-test was 0.84 (CG) and 0.88 (EG); whereas for the post-test was 0.83 (CG) and 0.77 (EG). In all cases, the scores were above 0.7, an acceptable value to judge the efficiency of the questions for examining the subject in question (Tavakol & Dennick, 2011). Accordingly, Levene's test was performed for both the pre- ($p = 0.09$) and post-test ($p = 0.11$) scores to examine the homogeneity of variance. The test showed that the results did not achieve statistical significance, allowing us to conduct additional analysis. The independent *t-test* performed for the pre-test results indicated no statistically significant differences between the two cohorts ($t = 0.80$, $p = 0.43$). As a result, we can conclude that both groups had similar competencies (knowledge base) before conducting the intervention.

TABLE 2 Experiment design

Week	Procedures	Operations
1	Grouping	Participants were assigned in one of the two groups based on the responses provided prior to the conduct of the study regarding their experience with digital learning tools
2	Pretest	Students were requested to complete a pen-and-paper knowledge quiz independently. This activity lasted approximately 30 minutes
	Presentation	A brief session related to different innovative technologies (interactive books/videos, Virtual/Augmented Reality) and their potential in education was given to all students as a compensation for their willingness to participate in this study. This activity lasted approximately 60 minutes
3	Lecture	Students were given a brief lecture about the human heart anatomy from the ME expert. This activity lasted approximately 30 minutes
	Activity	Students were split in separate 'breakout' rooms (Zoom platform). The immersive technologies expert performed a brief demonstration (orientation session) to the experimental group students related to the integrated AR application. The control group students engaged with the course material via the digital handout notes. The ME expert and the researcher supervising the process were shifting across the rooms ensuring that students' concerns would be addressed. This activity lasted approximately 45 minutes
4	Posttest	Students were requested to complete the same test used for the pretest. The order of the questions/items has been altered to prevent memorisation of answers. This activity lasted approximately 30 minutes
	Questionnaire	Students were requested to complete the training satisfaction questionnaire. This activity lasted approximately 5 minutes

By extrapolating the results in Table 4, a positive observation regarding students' knowledge advancement can be made. To explore this argument further, we plotted students' performance (Figure 7) and conducted paired *t*-tests. The results show significant difference between the pre-and post-test scores for the EG ($t = 4.61$, $p < 0.05$), but no significant difference for the CG ($t = 0.88$, $p = 0.3782$). Because of these results, we performed a two-sample *t*-test to confirm the significance of improvement between the cohorts ($t = 0.43$, $p = 0.003$) and utilised Cohen's *d* value (0.79) to determine the relative effect size, which is *large* (Diener, 2010).

Considering these results, we can conclude that the AR app contributed both significantly more to the development of students' knowledge and a greater degree when compared to the non-technological (traditional) approach. This is the critical finding from the study. The anecdotal feedback that we received about the realistic representations, which demonstrate how the human heart works, and the customised features that the AR app offered, may explain the outcome. On the other hand, the traditional didactic approach enabled students to study the main concepts but hindered the development of a deeper and more comprehensive understanding of the functions and operations of the human heart.

Learning satisfaction

To ensure the validity of the instrument, we conducted a reliability analysis (Cronbach's *a*) across all responses. The internal consistency coefficient (total score) was 0.96 for the CG and 0.79 for the EG.

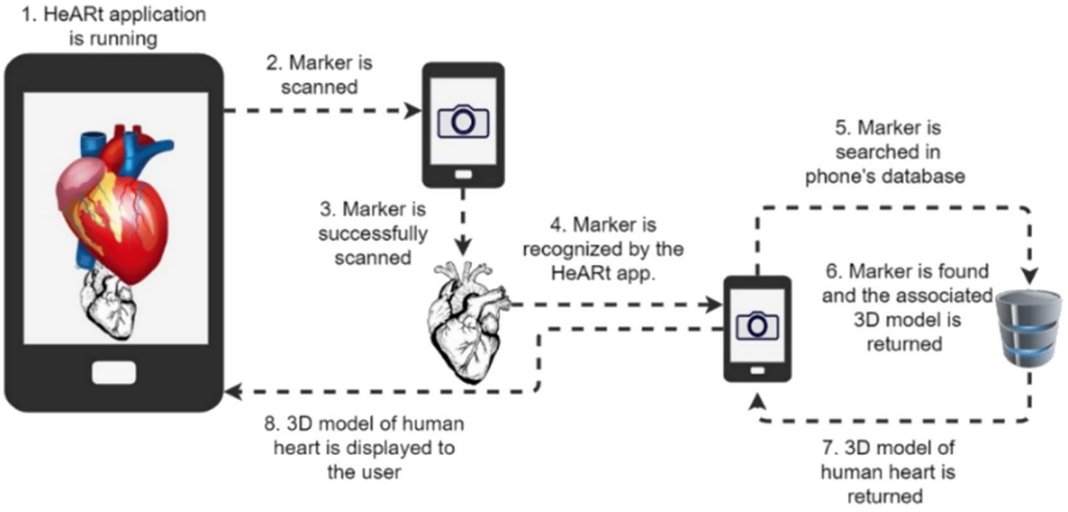


FIGURE 6 Main instructions

TABLE 3 Participants' demographic information

	CG		EG	
	N	**Percent**	***N***	**Percent**
Gender				
Males	17	56.67	16	53.33
Females	13	43.33	14	46.67
Age group				
18–24	19	63.33	18	60.00
25–34	8	26.67	8	26.67
35 and above	3	10.00	4	13.33
ME year				
First	16	53.33	11	36.67
Second	6	20.00	10	33.33
Third	8	26.67	9	30.00
English level				
Beginner	0	0.00	0	0.00
Intermediate	2	6.67	4	13.33
Advanced	10	33.33	14	46.67
Proficient	18	60.00	12	40.00
Use of digital learning resources (eg, Learning Management Systems, digital textbooks)/Mobile devices (eg, tablets, smartphones) for self-directed learning (eg, course podcasts, lecture webcasts)/other course-related activities (eg, note taking, presentations)				
Always	16	53.33	12	40.00
Often	11	36.67	15	50.00
Sometimes	1	3.33	1	3.33
Never	2	6.67	2	6.67

TABLE 4 Descriptive statistics for the quiz results

	Control		Experimental	
	Pretest	**Posttest**	**Pretest**	**Posttest**
Min	0.18	0.21	0.21	0.30
Max	0.79	0.94	0.94	1.00
Mean	0.53	0.57	0.48	0.73
Median	0.58	0.59	0.41	0.74
Std. dev.	0.18	0.20	0.22	0.17
Std. error	0.03	0.03	0.04	0.03

Note: To ease the presentation of the results, the scores have been scaled (min = 0, max = 1).

Students' perception of training satisfaction was initially explored by averaging the scores of participants' responses (individual items) across the corresponding constructs (Table 5). Across all clusters, the 'Learner Control' construct had the highest mean value, suggesting that the students of the EG appreciated the enhanced experience that the AR instructional approach offered. By contrast, the 'Self-directed Learning' construct had the lowest mean value, suggesting that the handouts provided a less satisfactory experience. The relatively smaller difference in the means of the 'Motivation for Learning' cluster, as compared to the means in C1 and C3, could be related to the wider impact that the pandemic outbreak had on students' willingness to engage with any form of activities, including educational ones. Considering the above, and the attitude that participants maintained toward these statements, we can conclude that both the degree of freedom and the opportunities for better learning afforded by the AR app impacted students' motivation in a more substantial way.

Since the MANOVA revealed a significant difference between the cohorts across all variables (Wilk's $\Lambda = 0.19$, $F = 20.30$, $p < 0.05$, $\eta^2 = 0.81$), we performed univariate F tests to explore the significance of the difference across the constructs (Table 6). The exploratory analysis confirmed the difference on students' satisfaction, with the EG maintaining a significantly more positive stance.

Given the small sample size, non-parametric tests (Mann-Whitney U test for the performance and Kruskal-Wallis H test for the satisfaction) were also applied, the outcomes of which confirmed the earlier observations (Table 7).

DISCUSSION

The findings provide evidence that the integration of AR in ME can become a valuable addition to practitioners' teaching modalities, especially in subjects akin to anatomy and physiology. The critical finding reported is that AR improves learning of ME materials over the traditional lecture approach. Such findings are consistent with previous studies (Dehghani et al., 2020; Zargaran et al., 2020), which indicated that, unlike the restricted intuitiveness that the two-dimensional graphic images in textbooks and handouts present, the 3D element that AR offers enabled learners to develop stronger spatial awareness related to the structure and functionalities of the anatomical components. Moreover, after accounting for the constraints imposed when considering the conduct of laboratory practices in ME (eg, the cost of specialised equipment, the need for monitoring and supervision), the introduction of alternative didactic solutions—even supplementarily—is justified.

Regarding *RQ1*, the knowledge assessment results demonstrated the significant potential of AR to promote both knowledge acquisition and retention, despite the difference observed in participants' knowledgebase during the pre-test. These findings are in line with

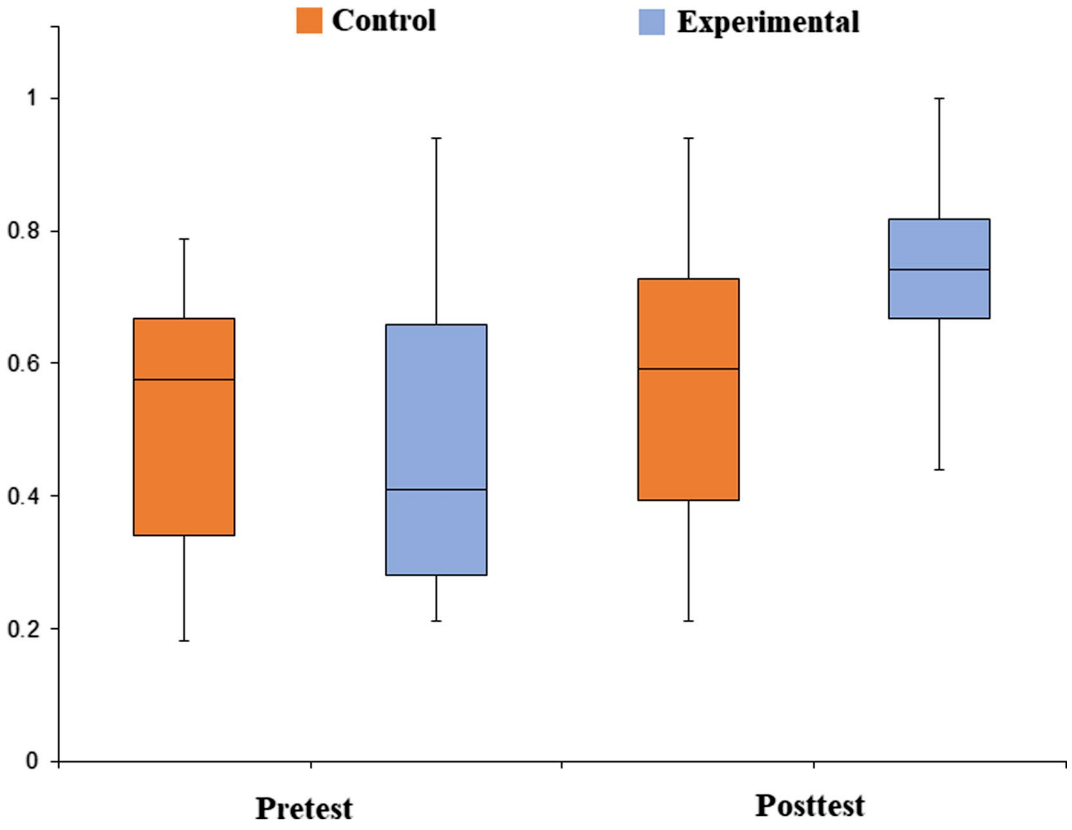


FIGURE 7 Comparison of participants' pre- and post-test performance

TABLE 5 Descriptive statistics for the training satisfaction questionnaire constructs

Construct	Variable	Group	Max	Min	Mean	Std. dev.
C1	Learner control	CG	5	2	3.22	0.86
		EG	5	3	4.26	0.65
C2	Motivation for learning	CG	5	1	3.29	1.23
		EG	5	2	3.88	0.61
C3	Self-directed learning	CG	5	1	2.83	1.02
		EG	5	2	3.76	0.49

previous studies (Dehghani et al., 2020; Moro et al., 2020; Vergel et al., 2020) suggesting that AR-supported interventions in ME courses bring flexibility without discounting the actual learning gains. Therefore, the integration of the supplementary AR-supported instruction enabled students: (a) to determine the order in which the elements integrated within the AR app were explored to make them more meaningful and memorable; and (b) to interact and view 3D multimedia content, which has been reportedly linked to better cognitive outcomes and engagement, especially when validating existing knowledge and developing new cognitive schemas via 'hands-on' actions.

Regarding *RQ2*, the *HeARt* app impacted positively not only students' performance but also their satisfaction. These outcomes are also consistent with findings reported in

TABLE 6 Summary of one-way MANOVA

Dependent variable	Grouping variable	Sum of squares	*df*	Mean square	*F*	*p*	η^2
Learner control	Group	48.05	1	48.05	27.49	0.00	0.32
Motivation for learning		21.00	1	21.00	5.59	0.02	0.08
Self-directed learning		38.27	1	38.27	19.97	0.00	0.25

TABLE 7 Summary of the non-parametric statistics

Performance comparison		
	Independent sample *t*-test	**Mann-Whitney *U* test**
Pre-test	*t*-test (*t*) = *0.80*	*u*-test *(u)* = 396
	t-test (*p*) = *0.43*	*u*-test (*p*) = 0.424
Post-test	*t*-test (*t*) = −3.09	*u*-test (*u*)= 258.5
	t-test (*p*) = 0.0030	*u*-test (*p*) = 0.005
Satisfaction comparison		
	One-way MANOVA	**Kruskal-Wallis *H* Test**
Learner control (C1)	*F* = 27.49	*H* = 18.43
	$p < 0.01$	$p < 0.01$
Motivation for learning (C2)	*F* = 5.59	*H* = 5.59
	$p = 0.02$	$p = 0.02$
Self-directed learning (C3)	*F* = 19.97	*H* = 13.79
	$p < 0.01$	$p < 0.01$

previous studies (Kiourexidou et al., 2015; Moro et al., 2017). However, some students may not be able to advance their knowledge owing to the natural restrictions that AR technology imposes. For instance, it may restrict a learner's ability to think in a way that allows them to translate abstract concepts into tangible knowledge and, therefore, transferable skills.

Despite this potential issue, AR-interventions can be of particular value to those students who have accessibility concerns, especially when educational practices are taking place purely remotely and any form of 'hands-on' experience is therefore missing. Under these considerations, it can be argued that the provided AR app for 'hands-on' training experience can foster knowledge acquisition and promote deeper disciplinary learning regardless of the spatiotemporal limitations that other approaches involve. Nonetheless, to achieve optimal results, such interventions should be administered during the students' preliminary stage of contact with the subject under investigation and only as a complementary method to traditional techniques.

CONCLUSION

In this study, we compared the educational impact and training satisfaction of AR-supported instruction against a more common approach used in the field of ME, supplementary handout notes. Even though the learning process took place purely online, the *HeARt* app increased the incentives for student-centred learning and enabled participants to achieve better learning outcomes and disciplinary understanding. On this basis, we conclude that the integration of 3D interactive content, using only students' personal mobile devices, can act as a countermeasure to the drawbacks that online teaching-and-learning practices naturally bring.

The contribution of this study is three-fold: (a) the proposition of a new approach to enhance the instructional process in the field of ME during online learning; (b) the provision of insights to researchers and educators regarding the impact of interactive 3D content in assisting students to apply abstract concepts without the use of discipline-specific physical aids; and (c) evidence on the conditions under which AR-supported educational activities can increase students' academic performance and satisfaction.

In terms of implications for practice and policy, we suggest that the learning material should be platform-independent. The structure of the lecture should be re-organised so that students can engage and interact with the respective supplementary method during the delivery of the learning content. The use of handout notes is also recommended as ME students are already familiar with this instructional method as it is being widely used during the revision and consolidation period. AR-based learning materials can also be combined with collaborative learning activities where students collectively explore and discuss the concepts under investigation and their relationships.

LIMITATIONS AND FUTURE WORK

The sample is insufficient to draw generalisable conclusions outside the study's context. The fact that the application was evaluated only in one country also affects the external validity of the results. Although efforts were made to mitigate the novelty effect, participants' attitudes toward the integration of technology in education and socio-cognitive norms may have been a factor in the variances in their academic performance and training satisfaction. Although this does not explicitly translate to selection bias, it restricted the conduct of a fully randomised selection. Finally, due to the enforced remote teaching setting, tracking in detail all students' interactions with the learning material that was not possible.

Future work should consider mixed-methods research design, over a longer time period, with larger sample sizes. By collecting data using diverse methods, researchers are more likely to reveal any drawbacks of the AR approach. Finally, the use of AR in other ME subjects may lead to the development of 'storytelling' scenarios, in which students can explore different topics in a more systematic and consistent way.

CONFLICT OF INTEREST

There is no potential conflict of interest.

ETHICS STATEMENT

Participation in the study was voluntary. Participants' personal information were not collected and the right to withdraw at any time was granted.

DATA AVAILABILITY STATEMENT

Anonymised data can be obtained upon reasonable request to the corresponding author.

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