Development of Three-Dimensional Interactive-Based Learning Systems for Basic Transthoracic Echocardiography Education

By

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ABSTRACT

In transthoracic echocardiography training, most medical trainees have difficulties achieving a conceptual understanding of spatial relationships between the echocardiography image and the complicated cardiac anatomical structures. A recent tradition of echocardiography training combines a traditional instructor-led workshop with self-directed online learning. In respect to the advance of educational technologies, the interest in three-dimensional (3D) visualisation has been widespread as it can be a part of the interactive learning systems for improving students' understanding of the complex phenomena in TTE.

Self-paced learning materials equipped with 3D visualisation components is the focus of this thesis. This study proposed methodological and technical aspects of 3D interactive learning systems development which were delivered through two techniques: a computer-based multimedia and an augmented reality (AR) application. This aim was to assess how medical trainees value these two 3D learning systems and what achievement they gain from their uses in reaching basic TTE comprehension. 46 resident doctors who were novice in TTE at the Faculty of Medicine Siriraj Hospital, Thailand were voluntarily recruited in the study. The result indicated that residents' knowledge gained from each learning system was similar. Comparably, no significant differences between learning systems were found in the usability questionnaire. Additionally, the responses to open-ended questions on experience highlighted a preference for the 3D graphical presentation of AR over the computer screen-based media. Finally, they anticipated that future versions of the AR application might be a mixed reality application equipped with a mock transducer probe for simulating actual TTE exam on a life-size mannequin.

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
A	Anterior
A4C	Apical Four Chamber
AAMC	Association of American Medical Colleges
ACCP	Advanced Critical Care Practitioner
AL	Anterolateral
AL	Anterolateral Papillary Muscle
AMVL	Anterior Mitral Valve Leaflet
AR	Augmented Reality
ATVL	Anterior Tricuspid Valve Leaflet
AV	Aortic Valve
AV	Augmented Virtuality
BJCA	British Junior Cardiologists' Association
BSE	British Society of Echocardiography
CAI	Computer-Assisted Instruction
CAL	Computer-Assisted Learning
CAVE	Computer-Aided Virtual Environment
CCE	Critical Care Echocardiography
CD-ROMs	Compact Disc Read-Only Memory
COVID-19	Coronavirus Disease of 2019
CT	Computed Tomography
DVD	Digital Video Disc

DICOM	Digital Imaging and Communications in Medicine
EACVI	European Association of Cardiovascular Imaging
EF	Ejection Fraction
EMT	Electromagnetic Tracking
FADE	Focused Assessment Diagnostic Echocardiography
FAST	Focused Assessment with Sonography for Trauma
FATE	Focused Assessed Transthoracic Echocardiography
FBX	Filmbox
FCU	Focused Cardiac Ultrasound
FEEL	Focused Echo in Emergency Life Support
FICE	Focused Intensive Care Echocardiography
GMC	General Medical Council
GUI	Graphical User Interface
HMD	Head-Mounted Display
HWD	Head-Worn Displays
I	Inferior
IAS	Interatrial Septum
ICE-BLU	Intensive Care Echo and Basic Lung Ultrasound
ICS	Intensive Care Society
ICU	Intensive Care Unit
IL	Inferolateral
IS	Inferoseptal
ISO	International Organization for Standardization
IT	Inertial Tracking
IVC	Inferior Vena Cava
IVS	Inter-Ventricular Septum

JPEG	Joint Photographic Experts Group
LA	Left Atrium
LLPV	Lower Left Pulmonary Vein
LMS	Learning Management System
LNA	Learning need assessment
LV	Left Ventricle
MCQ	Multiple-Choice Question
MR	Mixed Reality
MRI	Magnetic resonance Imaging
MV	Mitral Valve
NCC	Non-Coronary Cusp
OP	Optical Tracking
PET	Positron Emission Tomography
PLAX	Parasternal Long Axis
PM	Posteromedial Papillary Muscle
PMVL	Posterior Mitral Valve Leaflet
PSAX	Parasternal Short Axis
QEHB	Queen Elizabeth Hospital Birmingham
RCC	Right Coronary Cusp
RV	Right Ventricle
RV	Reality-Virtuality
RVOT	Right Ventricular Outflow Tract
RUPV	Right Upper Pulmonary Vein
RWMA	Regional wall motion abnormalities
S4C	Subcostal Four Chamber
SBE	Simulation-Based Education

SBLE	Simulation-Based Learning Experience
SME	Subject Matter Expert
SpR	Specialist registrars
ST	Specialty trainee
STL	Standard Tessellation Language
STVL	Septal Tricuspid Valve Leaflet
SUPR-Q	Standardised User Experience Percentile Rank Questionnaire
SUS	System Usability Scale
TAM	Technology Acceptance Model
TGC	Time Gain compensation
TTE	Transthoracic Echocardiography
TOE	Transoesophageal Echocardiography
TV	Tricuspid Valve
UI	User Interface
VATS	Video-Assisted Thoracoscopic Surgery
VR	Virtual Reality

Chapter 1
Introduction

1.1 Problem statement

Over the last decade, we have witnessed the exponential rise in use of technology in medical education. This trend stems from a great demand for paradigm shift in medical education to meet the challenges of disruptive changes in health care delivery, and a serious deficit of trained instructors or professionals (The Cochrane Collaboration, 2021). These also happened in transthoracic echocardiography (TTE) education as many studies identified and highlighted that a serious shortage of echo experts, time constraints, and access barriers (to certified trainers and echocardiographic machines) are significant and prevalent learning barriers for medical trainees (Jacques et al., 2017; Kydd et al., 2014; Morris et al., 2010). Thus, technology solutions that enhance learning opportunities and maximise students' engagement have become increasingly crucial in TTE education. Rapid advancement technologies infuse the traditional TTE training method with digital learning tools as a blended learning strategy. A typical example of blended learning scenario is that trainees are encouraged to attain theoretical knowledge—regarding cardiac anatomy, transducer indicator and orientation, and how to interpret TTE images—through online tutorials prior to attending a teacher-led class equipped with high-fidelity simulators (Price et al., 2008; Vignon et al., 2018).

According to recent studies, there are many modern technological devices used in TTE education, but augmented reality (AR) is seldom found. AR and its popular cousin, virtual reality (VR), are encompassed within immersive technology. The demand of AR/VR in healthcare education has grown tremendously as seen in many fields, such as human anatomy education (Bogomolova, 2020), and surgical training (Logishetty et al., 2019). The cutting-edge AR/VR solutions offer enhanced interactive visualisation, sometimes equipped with multiple sensory modalities, that can simplify the process of teaching and learning, and allows medical students to achieve a profound understanding of medical knowledge and procedure without the need for invasive intervention.

In echocardiography education, AR/VR adoption was firstly introduced in the 2000s with the typical objective of providing trainees with a high-quality visualisation and orientation guidance for improving their conceptual understanding of spatial relationships between actual ultrasound images and cardiac anatomical structures (Weidenbach et al., 2000). However, according to educational research studies, VR applications were utilised more often than AR. Besides that, those applications were not mainly intended for basic TTE training but for other specific interventions, for example, a live demonstration of paediatric echo examination (Sullivan et al., 2021), and imaging guidance systems for pre- and intraoperative procedures (Linte et al., 2007; Pushparajah et al., 2021).

Because, as mentioned above, research evidence of AR adoption for basic TTE learning is scarce, there is a need for such initiatives to be evaluated. Additionally, the investigation of the effect of digital technology on self-directed learning is an untapped area in TTE education. According to most studies, the blended learning approach—combining an introduction class with a hands-on demonstration session using either a commercial echo simulator or a live volunteer—was popularly used due to its effectiveness in promoting both knowledge and procedural skills of students. There is little to no research directly investigating the various digital three-dimensional visualisations used for self-paced learning activities and comparing their effectiveness on whether these improve medical trainees' understanding of basic TTE fundamentals.

1.2 Motivation

The motivations of this PhD research are:

- A growing demand for digital learning solutions promoting self-paced learning activities in medical education.
- In echocardiography training, medical students and novice doctors experience difficulty in understanding complex spatial relationships between the echocardiography image and the actual structure of the heart anatomy.
- Insufficient research findings about the application of human computer interaction (HCI) and human-centred design (HCD) in the context of technology-enhanced learning in echocardiography education
- Insufficient studies at present reporting the implementation of the cognitive-related theories for designing instructional media in echocardiography education.

- A lack of a useful framework for investigating how 3D visual presentation in technology-mediated learning tools affect students' learning outcomes and their affective feelings.
- No prior production pipeline for applying the usability metrics to measure students' satisfaction with digital learning tools in echocardiography education.

1.3 Research questions

By considering the mentioned findings, the author proposes the experiment for assessing the influence of digital technologies for self-paced learning on the increasing knowledge about basic transthoracic echocardiography (TTE) and determining how the bespoke learning tools provided by the author meet medical trainees' expectations. This research attempts to answer the following questions (Q):

Q1 What are the current educational technology trends that are supporting TTE education?

Q2 How familiar are medical trainees with augmented reality technologies and applications?

Q3 How does visual representation fidelity in technology-mediated learning tools affect their understanding about the complex spatial relationships between the TTE image and the cardiac anatomy?

Q4 How does visual representation fidelity in technology-mediated learning tools affect user acceptance and usability?

1.4 Aims and objectives

The overall aim of this thesis is to investigate the effectiveness of two different learning media prototypes, a computer-based multimedia instruction and an augmented reality (AR) application for self-directed learning activity in basic transthoracic echocardiography (TTE) education. The investigation focuses on whether 3D graphic presentation and degree of immersion implemented differently in each of the proposed learning media cause different learning outcomes in relation to students' knowledge improvement and affective feedback regarding the usability and user acceptance. To achieve this aim, the specific objectives (OBJ) are set as follows.

OBJ1 Inspect the existing studies regarding current adoption of technology-mediated learning tools in TTE education.

OBJ2 Apply the methods of human computer interaction (HCI) and human-centred design (HCD) to aid the design and development of learning media prototypes—an augmented reality application and a computer-based (non-web-based) multimedia instruction—which are employed for the study intervention.

OBJ3 Design and create tailor-made 3D anatomical graphics which are utilised in the proposed media prototypes which can provide a rich data visualisation about the four basic TTE images—parasternal long axis (PLAX), parasternal short axis (PSAX), apical four-chamber (A4C) and subcostal four-chamber (S4C).

OBJ4 Perform a learning experience survey with the rationale to address the target participant's prior background in echocardiography examination and their familiarity with novel technology-mediated learning tools.

OBJ5 Investigate the effectiveness of 3D visual presentation implemented differently in each of the learning media prototypes on medical students' knowledge improvement.

OBJ6 Evaluate the usability and user acceptance of the proposed leaning media by medical trainees.

1.5 Theoretical framework

1.5.1 Human computer interaction and design principles for learning technologies

Throughout computing history, the early stages of the technology of modern computer were recognised in the 1930s. Until the late 1970s to the 1980s, modern computers were no longer limited for only academic or professional use in the specialized laboratory but also available for the public and personal use. With the emergence of personal computer (PC), people who specialised in computer science realised how to design and implement computer systems that satisfy non-expert users, then the concept of Human-Computer Interaction (HCI) became apparent (Ristanović and Protić, 2012). According to the Association for Computing Machinery (ACM), HCI is "a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them" (Hewett et al., 1992). HCI fundamentally pinpoints three intersecting components: a user, a computer and a medium that enables communication between any user and a computer—called an interface. The aims of HCI are to develop computer systems or digital products which deliver effective, safe and easy-to-use interactive interfaces that satisfy users' needs (Issa and Isaias, 2022). In summary, the HCI principle continues to thrive across many subjects covering computer science, behavioural science, cognitive science, human factors, design principles, and psychological science. (Caroll, 1997; Meyer and Norman, 2020).

For ensuring that computer interactive systems are designed to focus on user experience with effortless interaction, human-centred design (HCD) has emerged as a central concept within HCI. HCD principle basically aligns with the application of ergonomic task analysis, usability knowledge and techniques to make usable and useful interactive systems based on user-driven requirements and their limitations (ISO 9241-210:2010, 2015; Karat and Karat, 2003). There are four HCD activities that should be considered throughout the design of any interactive system. These include understanding and specifying the context of use, specifying the user requirements, producing design solutions and evaluating the design (Gulliksen, 2003). In order to integrate HCI into the design and development process of any interactive based system, Hewett et al. (1992) suggested that researchers and developers should consider some attributes which are underlying impacts on interrelationships between a human and a computer system including context of use, human characteristics and computer system and interface architecture.

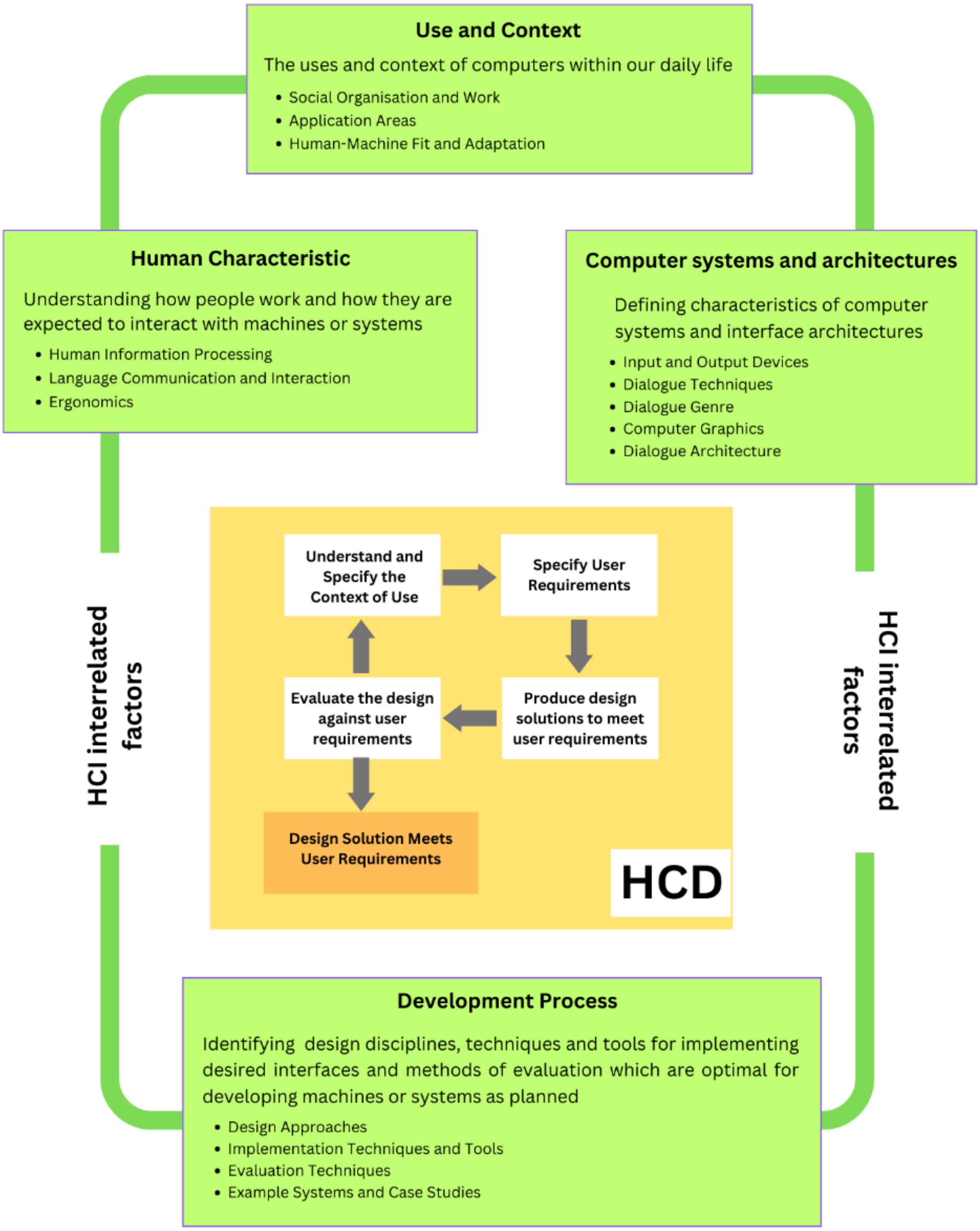


Figure 1.1: Framework for the development of interactive systems based on human computer interaction (HCI) factors and a design cycle of human centred design (HCD) (This diagram is adapted from the ACM SIGGHI Curricula for HCI) (Hewett et al., 1992)

The idea of applying HCI principle has become a key part of creating a wide range of products and applications such as mobile devices, smartphone applications, and learning materials (Alnanih and Ormandjieva, 2016; Darin et al., 2019; Mahdi, Naidu and Kurian, 2019). Educational technology is one of the notable examples which continues to apply the HCI principle to its development. Educational technology is particularly defined neither as only software application nor as the hardware implementation, but as an approach incorporating the use of technological media in an instructional method—or environment—for enhancing student learning achievement in regard to the planned learning objectives (Grayson, 1972). Over the last decade, a wide range of cutting-edge technologies have emerged that can have a significant impact on challenges and transitions for educational technology. By focusing solely on medical education, advances of digital technologies—including interactive multimedia, immersive learning applications and simulators—have evolved to facilitate the relationship between learner engagement and teaching effectiveness (Luc and Antonoff, 2016; Jiang et al., 2022; Liao et al., 2022).

Many such examples show how the HCI principle makes a significant contribution in current practice of technology-based learning in medical education. For instance, a study of Stuij et al. (2018) proposed the design framework for applying an online learning platform in oncology counselling support. They emphasised that the user requirement and attitudes should be prioritised over technology. As a result, healthcare professionals taking part in the study were asked to give their feedback regarding challenges in their clinical practice for patient education rather than the specifications of software or system of the learning module. Another interesting HCI aspect is the nature of human factors and human communication. In this perspective, the study by Koutsabasis et al. (2011) demonstrated that students' capabilities and limitations—both mental and physical—can be associated with their perceived attitudes towards learning techniques. For example, recent learners are the digital natives whose early development has been infused with internet and digital technologies. Therefore, they prefer learning with online platforms with well-established graphical elements and interface design for easy reading on screen, rather than reading textbooks.

In summary, digital technology has been a crucial part in medical education reform. Thus, HCI has also become the key principle for designing learning tools and systems with better solutions which respond to a variety of unmet needs of students. However, the implementation of HCI for medical education needs to be carefully considered because there are many factors that have constantly challenged educators and students in their daily practices, including the differences of learners' preference about how they learn and training time limitation. Therefore, educators or instructional designers must scrutinise in-depth their current courses and apply HCI strategies tailored to achieve the learning tools and systems they desire.

1.5.2 Human cognition-related theories and their application to instructional materials design

In human learning, the terms 'information' and 'knowledge' are closely related. Humans are designed to receive information from their five senses—sight, sound, taste, smell and touch—through the nervous system (Craig, 2007). Recent understandings of the human brain structure and function have arisen from the convergence of findings from a long history of research. The cognitive information processing (CIP) model by Miller et al. (1956) pioneered the development of cognitive theory describing how the human brain processes information which is received from the senses. The CIP theory focuses on a sequence of processing system regarding how the information is managed into the different stores of memory (i.e., sensory memory, short-term memory, and long-term memory); what kind of mental activities take place in each phase for transferring information from one memory store to another (i.e., attention, perception, repetition, coding, storing, and retrieving); and how each person has an awareness of his or her cognitive strengths or limitations in learning (Sternberg, 2008; Çeliköz, Erişen and Şahin, 2019).

In human cognition, a learning process occurs when humans can detect and make patterns in their brains for integrating the newly received information with their existing knowledge. The successful knowledge construction can take place when information is transferred from the sensory or the short-term memory to the long-term memory (Sweller, 1988; Clark, Nguyen and Sweller, 2006). Moreover, numerous cognitive science studies have a consensus that learners' emotions—such as interest, passion, engagement, and joy—have a substantial impact on the knowledge retention in long-term memory (Tyng, et al., 2017; van Kesteren, Krabbendam, Meeter, 2018).

CIP theory is often mentioned in connection with the cognitive load theory (CLT). CLT, firstly coined by Sweller (1988), focuses on how the human cognitive architectures of the working memory and long-term memory impact upon human learning. The working memory has a limited capacity which is only able to hold a small chunk of information at any one time, whereas the long-term memory has an indefinite storage capacity for collaborating with the working memory to process the retrieved information (Sweller, 2010; Reese et al., 2016).

Cognitive load theory is divided into three types including intrinsic load, germane load, and extraneous load. Intrinsic load relates to the difficulty of instructional contents which students must learn. Germane load refers to the cognitive load induced by instructional activities in the learning process. Extraneous load can be caused by the use of instructional material which does not help students to interpret and understand learning information (Clark, Nguyen and Sweller, 2006; Mestre, 2012). In summary, teachers and instructional designers should implement instructional systems that avoid cognitive overload by applying some strategies, for example, increasing the germane load by providing students with examples connected to real-life situations, reducing the intrinsic load by classifying the learning contents into the smaller chunks of information, and reducing the extraneous load by only including keywords and critical contents in the instructional presentation without unnecessary information or unrelated graphics (Clark, Nguyen and Sweller, 2006; de Jong, 2010; Mayer, 2017).

In general, the implementation of technology to enhance learning is useful in many ways such as supporting conventional classroom-based learning, engaging students with new types of learning experiences, and reducing the workload of the instructor (Lim and Morris, 2009). A main recommendation from many research studies is that teachers—or instructional designers—should have a sense of how the cognitive load theory can be applied within their instructional strategies for delivering learning media and materials to their students. The effective design of technology applications in learning processes should maximise germane load while minimising the amount of intrinsic and extraneous cognitive load (Ayres & Paas, 2007; Sweller, 2019; Skulmowski & Xu, 2021).

Until recently, several learning media design principles based on the cognitive load theory were developed. Most are aimed at guiding instructors in how to use digital learning media to maximise learners' achievement and manage learners' cognitive load effectively. For example, the cognitive theory of multimedia learning (CTML) is firstly coined by Richard Mayer (Moreno and Mayer, 1999). The basic premise of CTML is that people can learn more deeply from words and pictures than from just words alone. The theory can be divided into three assumptions. Firstly, the human brain has two separate channels for processing information presented in learning materials. The visual-pictorial channel is for processing printed words, videos, images, or charts, whereas the auditory-verbal channel is for processing spoken words and non-verbal sounds. Secondly, each channel has a limited capacity which can only process a finite amount of information at a time. And thirdly, multimedia materials should be used for stimulating learners' active cognitive processes, i.e., selecting relevant images and words from the presentation, organising the selected images or words into visual-pictorial or auditory-verbal models, and integrating that new information with prior knowledge (Fiorella and Mayer, 2021). In recent years, the technology of learning multimedia has rapidly evolved which can accelerate learners' interactions, using more senses and enjoying more immersion, e.g., immersive virtual reality. In this regard, the cognitive affective model of immersive learning (CAMIL), Figure 1.2, was developed for clarifying how affective and cognitive domains impact upon learning with immersive technology. According to the CAMIL, the interactive immersive digital environment can elevate the learners' experience in regard to procedural knowledge or psychomotor skills training. However, the instructors should be well aware that some unrelated interactive features and flourishing 3D imagery can hinder learning and increase the level of intrinsic motivation and extraneous cognitive load on learners (Makransky and Petersen, 2021).

Many studies in medical education have observed that the theories based on human cognition (e.g., CLT, CTML or CAMIL) were not implemented in designing instructional materials as they could have been (Yue et al., 2013; Hadie et al., 2016). A study by Yue et al. (2013) provided some cases of the ineffective interactive features and interface design of multimedia which were not user-friendly enough, for example some online lectures showed visual graphics disturbances or having unnecessary background music. Some medical animations or videos offered too much information to absorb in a single viewing (Yue et al., 2013). This point of concern has encouraged recent researchers to take a broader exploration by using the frameworks from cognitive load-related theories to improve the effectiveness of instructional materials used in medical training. Recently, substantial evidence has demonstrated that the well-prepared strategies of learning media design based on human cognition-related theories can impact learning through reducing cognitive load and promoting a better learning outcome (Song et al., 2014; Leppink and Duvivier, 2016; Hadie et al., 2016)

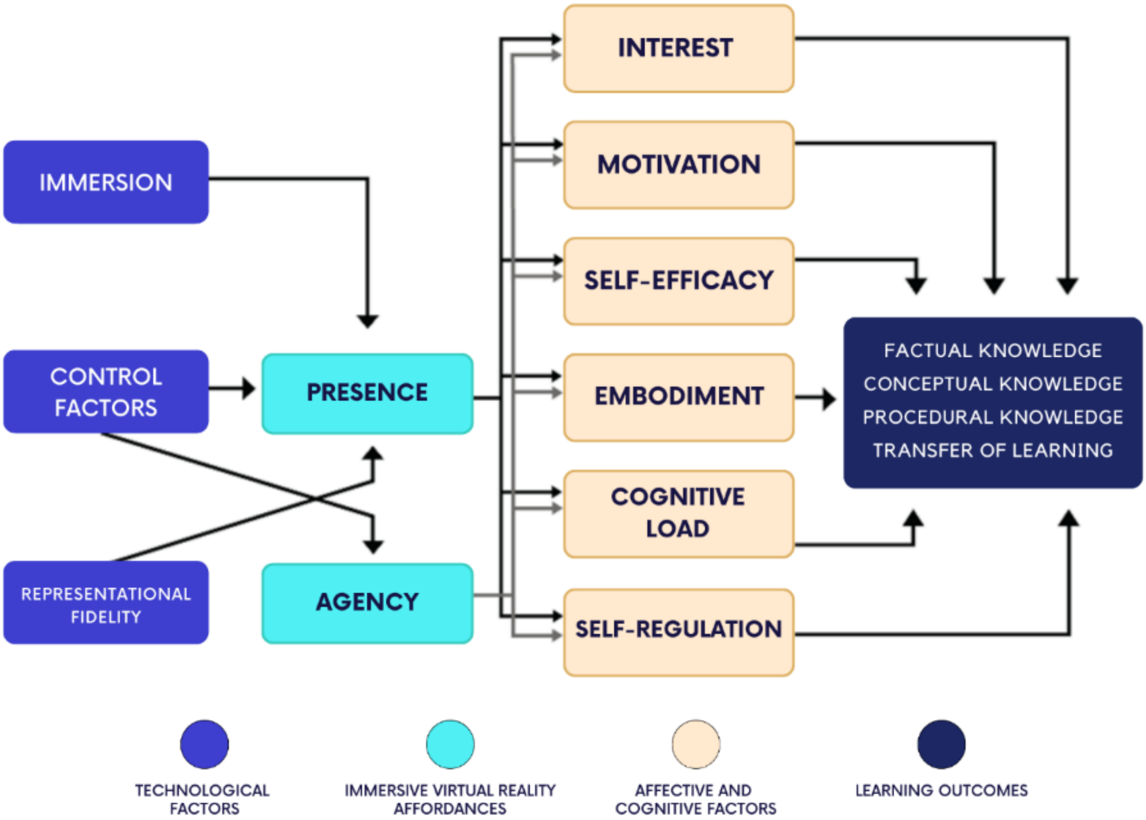


Figure 1.2: The CAMIL model proposed by Makransky and Petersen (2021).

1.6 Background of digital learning technologies

1.6.1 Augmented reality

1.6.1.1 History and definition

Augmented reality (AR) has become one of the most frequently mentioned technologies in the last decade. A succinct explanation of AR is as a set of technologies which increase the user's perception and interaction by superimposing digital information on top of the physical environment (Carmingiani and Furht, 2011). AR is regularly mentioned along with virtual reality (VR) and mixed reality (MR) under the umbrella term of immersive technology. AR is not a novel innovation, but in fact it has been around for longer than most people recognise. Since the first head-mounted displays (HMDs) for three-dimensional (3D) visualisation called the “Sword of Damocles'' was invented by Professor Ivan Sutherland and his team in 1968, AR technological progress has been so rapid. Its fascinating technology has been transferring from the laboratory to the commercial marketplaces and various industries (Höllerer and Feiner, 2004). According to the 2020 Augmented and Virtual Reality Survey Report, immersive tech has played a huge role in transforming the technology adoption in numerous industries— the top five rankings (excluding gaming and entertainment industries) are healthcare and medical devices, education, workforce development and training, manufacturing, and automotive (PerkinsCoie, 2020).

The term ‘Augmented reality’ was firstly coined in 1990 by a Boeing researcher, Thomas P. Caudell (Mekni and Lemieux, 2014). In recent technology terms, AR is one of the types of extended reality (XR). XR is an emerging term encompassing all immersive technologies—including virtual reality (VR), mixed reality (MR) and AR (Çöltekin et al., 2020). Before the term of XR entered widespread usage, there was a pioneering framework named *The Reality-Virtuality Continuum* (Milgram and Colquhoun, 1999) which has been cited by many researchers for decades (Fig 1.1).

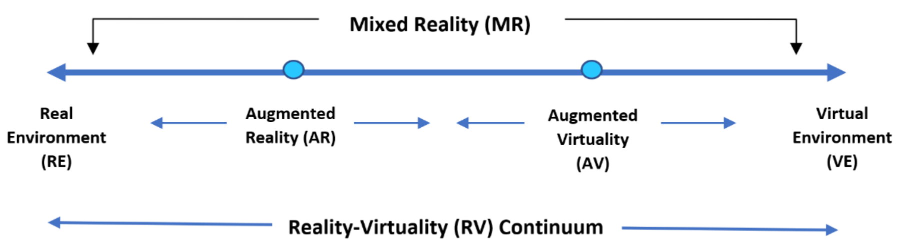


Figure 1.3: The diagram of Reality and Virtuality Continuum (Milgram and Colquhoun, 1999)

This two-sided spectrum portrays the boundary of user experience between real environment (RE) and virtual environment (VE). In contrast to the physical world, virtual reality (VR) immerses a user into a fully artificial or simulated environment. Current trends in software and hardware technologies influence users' or VR developers' decisions in choosing appropriate platforms for their purpose. A VR scenario is typically delivered through a headset (e.g., Samsung Gear VR, HTC Vive or Oculus Rift) for single users, and a set of multiple projectors—widely known as the CAVE (Computer-Aided Virtual Environment)—which is provided for multiple users. Within a VR environment, users will have the feeling that they are part of the virtual surroundings based on visual and auditory perception and will have no visual or tangible interaction with the real world. Whenever wearing headsets, the real world is replaced with a virtual one (Immersive Virtual Reality, 2008; Webster and Dues, 2017).

According to the Milgram's spectrum, AR is placed closer to the left pole of real environment than augmented virtuality (AV). Whereas VR completely blocks out the physical world, AR supplements reality by overlaying digital data and images. Since the Reality-Virtuality (RV) continuum was published, there have been several attempts to define key characteristics of AR application. Milgram, as the creator of the RV framework, proposed the idea of classifying virtual environments by types of displays. He described a variety of devices used for coexisting representations of real objects and virtual data. Ideally, the physical surroundings should be viewed directly through air or transparent devices; therefore, the key term *"see-through capability"* is employed to refer to an important characteristic of displays for AR systems (Milgram and Kishino, 1994). In 2001, Azuma and his team discussed the characteristics of AR devices in more details and categorised them into three types as follows.

i. *Head-worn displays (HWD)*

Wearable displays which are integrated into eyeglasses or mounted on a helmet. These devices augment users' vision with either optical see-through feature or video see-through feature.

ii. *Projection-based displays*

A technique of projection whereby virtual elements is projected directly onto the physical objects. Ideally, a virtual augmentation environment would appear to the user via a single room-mounted projector or a retinal direct projection head-mounted display.

iii. *Handheld displays*

A set of flat-panel displays equipped with a camera for video see-through-based augmentation (Azuma et al., 2001). This can be called mobile AR (Billinghurst and Henrysson, 2006: Research directions in handheld AR). Recent distinct classes of commercially available handheld AR displays are smartphone, tablet and personal digital assistant (PDA) (Wagner and Schmalstieg, 2006 : Handheld augmented reality displays).

Although display technology is the key criterion to define AR application, some researchers realised it does not include all essential components of AR. Azuma et al. (1997) suggested that the definition of AR should encompass any interactive experience associated with these following characteristics:

I. Combines real world and virtual elements—both should coexist;

II. Interactive in real-time—virtual contents can be interacted with;

III. Three-dimensional (3D) registration—spatial relations between the real and virtual objects.

Over the last twenty years, there has been some confusion about the definition of AR. A notorious misconception holds that it is similar to VR. Although VR and AR do share some similarities, such as the use of 3D graphics, and a collection of tools and software for development, they are not the same and are not able to be used interchangeably (Peddie, 2017). There are many possible sources for the development of misunderstandings. For example, both AR and VR share a common term of headsets, or HMDs, as the display device, but they have differing requirements for utilisation. Headsets are essential for VR systems, while they are not necessary for AR. The key difference between AR and VR Headsets is the opacity property. VR headsets are opaque, used for replacing the user's vision with a replica of the physical world or a novel synthesised environment (Webster and Dues, 2017); on the contrary, the user can see virtual objects superimposed into physical world through transparent AR displays (Aukstakalnis, 2016).

Besides the different types of headsets, some researchers investigated the difference of user interaction design between AR and VR. Caudell (1995) highlighted that graphical user interfaces being represented in AR are not as complicated as in VR systems. AR enables users to achieve an easy interaction with 3D objects or text with a simple wireframe overlaid onto the real world. In contrast, a fully immersive VR experience requires a lot more effort to develop, since the developer has to create an entirely new virtual world from scratch (Niu, 2016).

1.6.1.2. Recent adoption

Over the past few years, extended reality—especially AR and VR— has become one of disruptive technologies that are expected to shape the future in several industries. This technology captures users' attention in many sectors such as science and engineering, health and medicine, aerospace, education, or entertainment (Aukstakalnis, 2016). In 2018, the Harvard Business Review (HBR) Analytic Services conducted a survey of 394 executives and found that 87% of large companies are currently exploring, piloting, or deploying mixed reality (MR). Main objectives of AR and VR adoption have been linked to promoting engagement strategies, i.e., enhancing customer experience, increasing employee productivity, and presenting unprecedented products or services. In addition, respondents identified the three most important MR functions which have been deployed into their daily works, i.e., training/educating employees, visualising and analysing data, and assisting customers or employees remotely (Harvard Business Review Analytic Services, 2018). A latest report by Businesswire, launched during the global pandemic of coronavirus, stated that the global AR and VR market size is projected to reach USD 125.19 billion by 2024. Whereas many industries have experienced a negative effect associated with the change of customer behaviour during the Coronavirus disease of 2019 (COVID-19) outbreak, the demand for AR and VR applications has been increasing (Businesswire, 2020).

A variety of studies and surveys regarding recent technology adoption pointed out that users are likely to prefer AR than VR (Peddie, 2017; PerkinsCoie, 2020). The reason behind the users' positive attitude towards AR is that it offers an unprecedented digital experience which does not block them out from the real world like VR. This means that AR makes the users feel more comfortable with seamless interaction between virtual objects and the real world. Moreover, users also express their concern about cumbersome equipment and the time-consuming aspects of use and maintenance. As some people may have headsets-related discomfort, they may not appreciate using VR. In this context, AR adoption is more manageable. Users can be provided with a wide range of AR applications delivered with the user-friendly devices such as smartphones, and tablets (Niu, 2016; Sergiu, 2019). In summary, AR adoption has seen exponential progress and gained popularity over VR due to the advancements of mobile technologies (PerkinsCoie, 2020; Qualcomm, 2016).

Through the education industry, AR has been widely deployed across various educational stages—ranging from K-12 education (Maas and Hughes, 2020; Teichner, 2014) to higher education or vocational education (Martín-Gutiérrez et al., 2015; Webel et al., 2013). Wu. Lee, Chang, and Liang (2012) pointed out that the utilisation of AR in education should be firmly grounded on the principle of technology design, instructional approach, and learning experiences. By comparing with traditional learning methods, AR applications could promote greater student satisfaction and learning outcomes and help to reduce learners' cognitive load during their learning process (Billinghurst and Dünser, 2012; Bujak et al., 2013). A blended AR environment—the insertion of 3D visualised information into existing learning materials—can clear out some common learning misconceptions. For example, several studies proved that students' understanding and critical abilities towards the complex scientific concepts were positively enhanced after their self-paced learning with mobile AR applications (Cheng and Tsai, 2013; Faridi et al., 2020; Kurniawan, Suharjito, Diana and Witjaksono, 2018). AR not only improves the existing learning modalities, but it also offers new ideas or a new approach for bridging the gap between students' needs and learning experience, for example, creating a more inclusive learning environment through wearable AR systems for students with movement disorders (Arvanitis et al., 2009). In addition, other studies of AR for higher/professional education have found that it can increase productivity of trainees. By using AR, trainees can receive 3D visual work instructions without turning to manuals. They can easily transfer their procedural knowledge to real-world tasks. So, less time will be spent (Webel et al., 2013). Furthermore, the integration of AR into training systems has also been shown to reduce the learning curve of trainees, to encourage technicians to retain their skills and knowledge in a safe environment, and to help avoiding possible errors (Hou, Wang, Bernold and Love, 2013).

By focusing on the main landscape of this thesis—medical education, the benefits of AR have been quickly becoming an important part of medicine for the past decade (Aukstakalnis, 2016). The reason for its popularity is the ability to serve students' and medical professionals' needs for rich learning experiences for improving their clinical performance (Peddie, 2017). It has been widely discussed by health care professionals in regard to transfer of learning. Most of the training programs were designed to be ideal in nature, but somehow were imperfectly applied to the real situations. Medical trainees may leave the training with a good score or a positive impact, but they subsequently encounter a huge disconnect when they try to implement their skills and knowledge gained by learning experience at their workplace. Hence, the intricate interplay between didactic learning and experiential learning, coupled with changes in technology, has been transformed to reinforce the better alignment of medical education, clinical practice, and health care service system (Scheele, 2012; Sklar, Hemmer and Durning, 2018)

Throughout the experiential learning, medical students are encouraged by instructors to be involved in every aspect of constructing their knowledge and skills. In this way, modern technologies play a huge role for boosting students' or physicians' engagement as well as preparing them for the rapid transformation of clinical practice or health care systems (Guze, 2015; Sheng et al., 2018). As mobile technology has appeared to make AR more affordable and user-friendly, it offers a wide range of transformative approaches for education/training and clinical practice (Eckert, Volmerg and Friedrich, 2018). The versatility offered by AR technology has allowed the development of applications for the experiential learning in various medical domains, for example, representing 3D visualisation that helps learners to cultivate better understandings of spatial relationships associated with anatomy (Bogomolova, 2020; Bork, 2019; Henssen et al., 2020; Moro, 2017), providing training opportunities to assure competence in the clinical setting (Bretón-López et al., 2010; Mousavi Hondori et al., 2013; Lamounier et al., 2010), and offering alternative ways for acquiring and strengthening complex surgical skills (Logishetty et al., 2019; Rochlen et al., 2017). A comprehensive use of ultrasonography can also potentially benefit from the use of AR, where the visualisation of real ultrasound images or 3D reconstruction of internal organs inside the patient can be embedded in a real physical environment. It allows medical personnel to better understand the spatial relationships between ultrasound images and anatomical structures, without the need for invasive procedures (Ebner et al., 2019; Zhu, Hadadgar, Masiello and Zary, 2014). The principal aim of this thesis focuses upon educational technologies for training in echocardiography—ultrasonography of the heart. Therefore, these technologies, including AR adoption, will be elaborated upon further in the next chapter, Chapter 2: Literature Review.

1.6.2 Computer-based multimedia instruction

1.6.2.1 Concept of multimedia instruction

The rationale behind the multimedia instruction is the integration of two learning elements which are verbal presentation (e.g., narration, on-screen text or spoken text) and visual presentation (e.g., photos, illustrations, static images, and animated images) for stimulating learning processes and knowledge retention (Mayer, 2014). A remarkable transformation of multimedia instruction started since the mid-1900s when computer technology advanced enough to offer learners interactive learning experiences. Therefore, computer-based multimedia instruction has been trending upwards in the educational industry for supplementing, but not replacing, traditional teaching methods (Merzouk, Kurosinski and Kostikas,2014; Nagy, 2005; Nicholson 2007; Mayer 2014).

The concept of multimedia instructional design is based firmly on the cognitive theory of multimedia learning (CTML) (Moreno and Mayer, 1999; Mayer, 2014). In brief, the CTML pinpoints that more effective learning can occur when information is presented in both text and graphics than by text alone. The information which the learner receives from the multimedia instruction is separately processed by two different channels for learning: auditory and visual channels. Information processing starts in sensory memory, constructs the knowledge in working memory, and eventually integrates new knowledge with prior knowledge in long-term memory. According to the CTML, the learning process is presented in Figure 1.4.

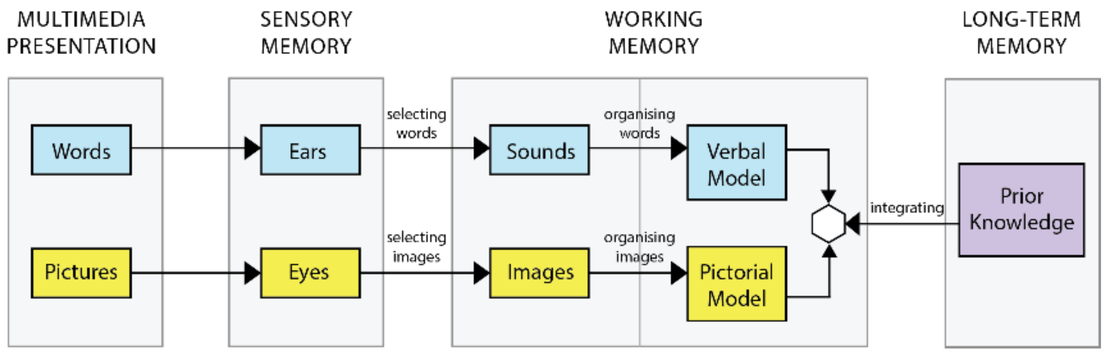


Figure 1.4: A Cognitive Theory of Multimedia Learning (Mayer, 2014)

In a generic sense, multimedia instruction is simply the combination of more than one media element. Text, audio, video, graphics and animation are the five basic elements of a multimedia learning environment. Multimedia simply combines these elements into a new learning medium (Guan et al., 2018). With recent advances in modern computer technology, the implementation of multimedia produces a more digital approach. It is often employed in electronic learning (e-learning) systems. In general, e-learning can refer to any digital instruction that is delivered via electronic devices being a part of the process of teaching and engaging students with specific content. There are a broad range of digital devices which can be used for e-learning purposes including laptop computers, desktop computers, smartphones, tablets, interactive whiteboard screens, game consoles, and head-mounted displays (Kapi et al., 2017; Mayer, 2017).

With the continuous development of Internet of Things (IOT) and information and communication technology (ICT), the methods that people experience with multimedia instruction are undergoing changes. This aspect leads educational scientists to define and categorise multimedia use as web-based and non-web-based multimedia instructions (Paul et al., 2016). Web-based multimedia instruction (WBMI), or online multimedia module, is accessible from anywhere as long as students have an updated browser with internet connection. Moreover, students can also effortlessly switch their devices—including smartphones, tablets, or computers—for learning without losing their current learning progress (Lau et al., 2018). In the domain of non-web-based multimedia instruction (non-WBMI), internet access is not necessary as the multimedia module is installed in the storage space on the desktop computer or a personal laptop computer. Although its function is not nearly as flexible and accessible as web-based intervention, non-WBMI offers some benefits regarding offline accessibility and more privacy. Overall, learning progress data is only stored on the learner's personal desktop or laptop computer (Wantland, D.J. et al., 2004).

Interactive computer-based multimedia instruction can be employed as a supporting medium in an instructor-led session or can be provided for student self-directed learning. For instructor-led training, the important aspect of multimedia instruction is to facilitate instructors with opportunities to control the pace of content delivery and provide immediate feedback to guide their students in the right direction (Gardiner, 2021; Merzouk, Kurosinski and Kostikas,2014; Paul and Jefferson, 2019). In self-directed learning strategy, it is often associated with asynchronous activities. Learners are only given the guideline or assignment required for achieving their study plan. They are then allowed to navigate through the digital multimedia courses at their own pace and schedule, based on their own preference. Many studies agreed that internet technology advancement—web-based multimedia instruction (WBMI)— is likely to enable truly flexible attributes of a more personalised learning approach. In summary, WBMI can provide more flexibility for students to set up their own learning pace and improves students' discipline with time management skills to keep up with lessons and assignments. However, due to the independent nature of WBMI, it may be challenging for students to maintain their learning motivation and find the networking opportunities with their instructor and other learners (Merzouk, Kurosinski and Kostikas,2014; Rigo and Mikuš, 2021; Shahabadi and Uplane, 2014).

1.6.2.2 Computer-based multimedia instruction in medical education

At the time of writing, the emerging technologies and the COVID-19 outbreak have become the most important growth drivers for the recent trend of web-based multimedia instruction (WBMI) adoption. As the pandemic is having a catastrophic effect on educational systems—a prolonged period of learning at home during school or university closures, there has been a significant demand for online learning. The latest data from the *Global Market Insights, Inc.* anticipated that the market size of online learning products and services is exponentially growing and set to exceed USD 1 trillion by 2027 (Wadhwani and Gankar, 2021). Recent technology has rapidly changed the possibilities within education by which teaching and learning do not need to be restricted to only traditional lectures or physical attendance (Duffin, 2020). The increasing use of WBMI can result from improved performance of networking systems and mobile technology. Therefore, many options have recently become available to students for accessing their online classes either by using high-quality resources and infrastructures at the university or accessing learning content on a smartphone or a tablet at their home (Chuang, 2009).

There has been a great demand for paradigm shift in medical education to meet the challenges of disruptive changes in health care delivery, a serious deficit of trained instructors or professionals (The Cochrane Collaboration, 2021), and students' burnout and exhaustion coordinated with their struggles to cope with a heavy load of work and study (National

Academies of Sciences, Engineering, and Medicine, 2019). Recognising the impact of innovative technology, the traditional teacher-centred approach has been transformed into students-centred and personalised education (Lewis et al., 2014). WBMI has become a current mainstream in medical education. In recent years more and more instructors have used it for developing their students' knowledge and skills (Ellaway and Masters, 2008; Huynh, 2017). In general, most medical students, or residents in training, always carry an overwhelming study schedule and a heavy load of clinical responsibilities and need to remain productive (Levey, 2001; Kuhlmann, Huss, Bürger and Hammerle, 2016). It is reported that online multimedia learning captures students' interest by providing a wider range of educational content, specifically in evidence-based clinical practice, than a traditional didactic approach. In addition, it also enables trainees to break out of strictly structured academic settings and give them the supplemental flexibility to complete dozens of lessons and tutorials at their own pace (Huynh, 2017; Al-Balas et al., 2020). Before delivering courses, medical instructors should assess themselves and identify their technological competencies, such as the ability to use and understand LMS (Learning Management System), and the ability to select the proper digital materials which are likely to best meet the expected outcomes for a particular learning context (Queiroz and Mustaro, 2003; Ellaway and Masters, 2008). Moreover, WBMI experience should be emphasised on learning competencies and circumstances. Some courses involve a focus on content whereas others focus on medical practice (Ellaway and Masters, 2008). Most self-directed online lessons are provided as mandatory programmes for building on foundations of medical knowledge (eIntegrity, 2020) or guiding effective communication skills (Vorstius Kruijff et al., 2016).

Although multimedia instruction attracts students' attention with its advantages over traditional classroom-based education, by providing a low-stress learning environment equipped with computer network technology, the use of pure multimedia instruction is still questioned. Several studies in medical education indicated that multimedia instruction cannot break some of the barriers perceived by instructors and students. For example, Anasel and Swai (2020) revealed several reasons why instructors were hesitant to integrate self-directed online multimedia instruction into their teaching plan. Most of the teacher's concerns centre around the technical issues, effectiveness of online lessons to replace traditional lectures, difficulties of getting real-time feedback from learners, and possible reduction of student self-motivation. Meanwhile, most students shared the opinion that they were satisfied with self-directed online multimedia instruction; however, interestingly, they did not agree that it can replace traditional instructor-led training (Ruiz et al., 2006). Moreover, students were concerned about the technical skill competency of medical instructors. They thought that some lecturers needed additional training about how to use digital devices and online course management for effective implementation of online learning modules (O'Doherty et al., 2018; Al-Balas et al., 2020).

In summary, with advances in technologies, a self-directed computer-based multimedia instruction has been adopted for training in the medical professions, ranging from medical students to health care providers. There is a wide agreement that integrated computer-based multimedia instruction modules in the form of blended learning strategies are now the norm in medical education. It is generally a complement to traditional lectures, laboratory-based training, and clinical ward-based practice. In a fast-paced and ever-changing technology, it is crucial for medical instructors to develop their use and understanding of multimedia learning technology. Technical skills need to be balanced with the expertise of establishing pedagogical content and managing learning materials so that medical teachers can offer the best possible computer-based multimedia course to their students.

1.7 Application of theoretical framework in research development

The theories of "human computer interaction" and "cognitive learning" are clearly central to this thesis. The framework related to human computer interaction (HCI) factors and a design cycle of human centred design (HCD) as shown in Figure 1.1 is used to aid the design and development of learning media prototypes—an augmented reality application and a computer-based (non-web-based) multimedia instruction—which are employed for the study intervention.

Various cognition-related theories have existed as previously mentioned in Section 1.5.2. This thesis draws on the CAMIL theory by Makransky and Petersen (2021). The main principle of the CAMIL framework clarifies relationship paths among technological factors, affordance of learning in immersive VR, affective and cognitive factors and learning outcomes. From the comprehension perspective of the CAMIL, this thesis narrows the scope down to a specific focus about how the representational fidelity of 3D graphic presentation in technology-mediated learning tools affects students' learning outcomes and their affective feelings, as shown in Figure 1.3.

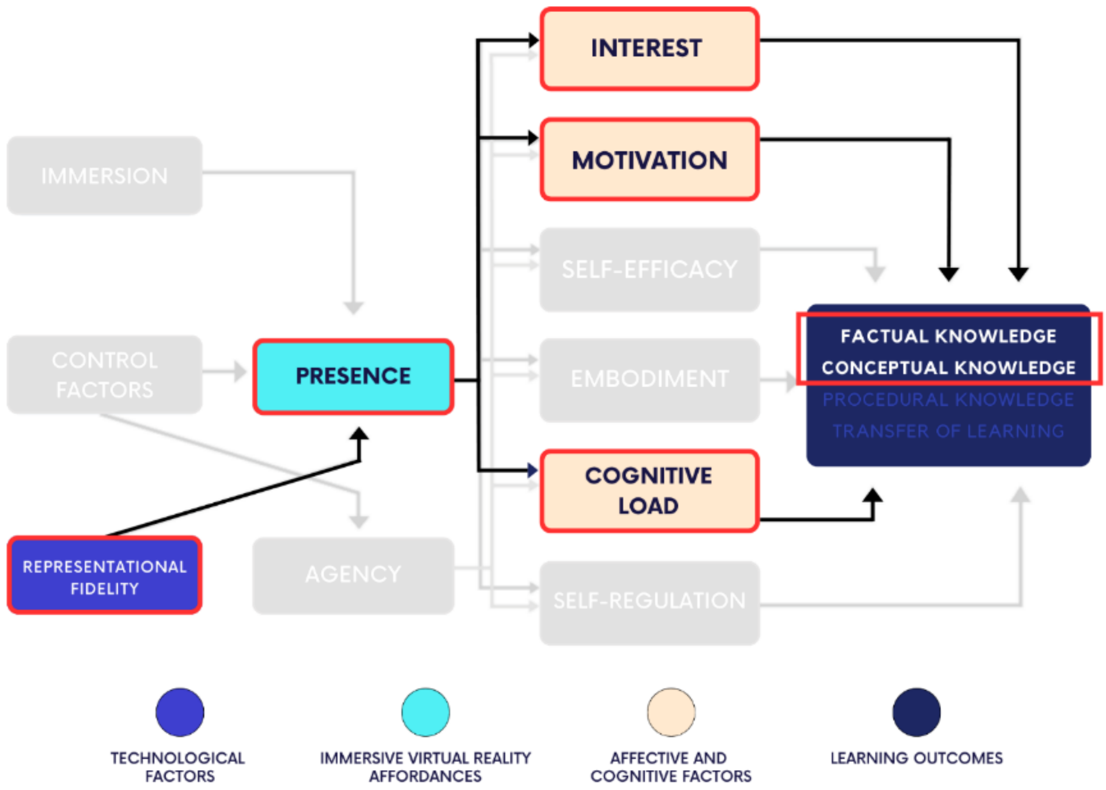


Figure 1.5: The thesis investigation' framework based on the CAMIL

Before the CAMIL framework's study, several studies have highlighted that visual representation fidelity in learning materials is considered as an important technological factor for learners to develop their mental representations leading to knowledge construction and memory processes (Cromley, Snyder-Hogan and Luciw-Dubas, 2010; Moreno 2006). Many factors can be involved in shaping representation fidelity in learning, such as display technologies, the perception of smoothness while interacting with the display, and the correspondence between the realism of visualisation and users' sensory (Dalgano and Lee, 2010).

According to the CAMIL, representational fidelity influences an experiential quality of learning in a virtual environment which affects a learner's feeling of presence. To investigate that how learning methods affect learning, the CAMIL proposed that there are six affective and cognitive factors which directly associate with learning outcomes including interest, motivation, self-efficacy, embodiment, cognitive load, and self-regulation. As such, this thesis only focuses the scope of investigation based on three factors —interest, motivation, and cognitive load.

In summary, two learning media prototypes—an augmented reality application and a computer-based (non-web-based) multimedia instruction, are designed to deliver different graphic representation fidelity to learners. Factual knowledge—bits of basic knowledge of terminology, and conceptual knowledge—complex structured knowledge (Anderson et al., 2001) of basic transthoracic echocardiography are defined as the required learning outcomes. The study intervention utilises the assessment instruments for analysing the causal connections between the affective and cognitive factors (interest, motivation, and cognitive load) and learning outcomes, as aligned to the CAMIL framework in Figure 1.3.

1.8 Thesis Structure

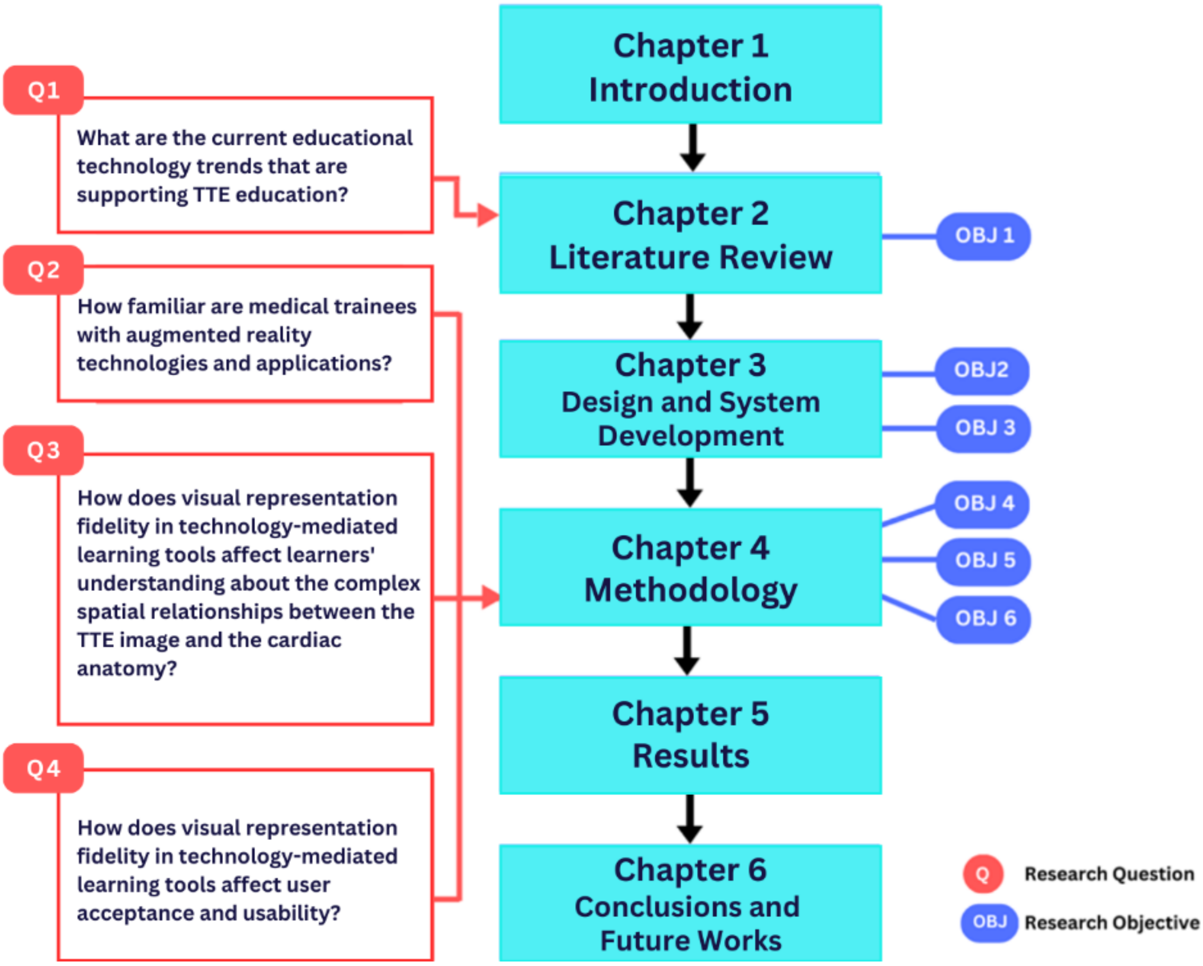


Figure 1.6: Thesis roadmap – Chapter 1

The thesis structure and its relationship with the identified research questions and research objectives are summarised in Fig. 1.5.

Chapter 2 provides a review of the literature relating to the common educational tools in echocardiography education with the focus on three technologies: web-based multimedia instruction, simulation, and immersive technology. The utility, specific features and limitations of each technology are discussed.

Chapter 3 is a full account of the design and development process of proposed educational media—the computer-based multimedia instruction and the marker-based AR application under the guidance of the theoretical framework mentioned earlier. The chapter starts with a brief overview of the Focused Intensive Care Echocardiography (FICE) course which is used as the benchmark educational model for the content preparation. This chapter also provides an in-depth overview based on the author's experience which was obtained from a hands-on TTE training participation conducted at the Queen Elizabeth Hospital Birmingham. This chapter also details the development of interactive 3D cardiac anatomical models which are consolidated into the systems for the computer-based multimedia learning module and the AR application. The last three sections of this chapter describe the system architecture of the computer-based multimedia instruction, the marker-based AR application, and an interactive set of web-based multiple-choice questions (MCQ) used as a tool for assessing the participants' knowledge gain.

Chapter 4 presents the overview, details, and the justification behind the design and features of the experiment based on the research aims. This chapter also describes the research methodology including a criterion and an approach for participant recruitment, experimental procedure, apparatus, and research instruments which were used for data collection.

Chapter 5 provides the results of the main experiment which are represented and analysed by statistical methods. An objective measurement of knowledge is assessed using the interactive MCQ pre- and post-test modules, whereas the subjective measurement is based on the participants' background, experience, and their usability feedback towards two learning methods.

Chapter 6 is the final chapter which provides the result interpretation and discusses the findings from the research. This chapter also includes a discussion of the limitation of the study and consideration for future works.

Chapter 2

Literature Review

2.1 Overview

The primary goals of technology adoption and implementation in medical education are promoting knowledge acquisition and retention, developing good decision-making skills, improving coordination and communication skills, enhancing psychomotor skill development, and preparing medical trainees to deal with difficult situations (Guze, 2015). For transthoracic echocardiography education, the use of technology has developed in response to facilitate a broader base of knowledge and procedural experience needed to perform an echo effectively. Many, moreover, are applied to solve the challenges associated with a serious shortage of echo professionals, time constraints, and access barriers (to certified trainers and echocardiographic machines) (Jacques et al., 2017; Kydd et al., 2014; Morris et al., 2010).

Based on the above challenges, this chapter explores the use of educational technology in TTE training in more details. Section 2.2 is the introduction part which explains the characteristic of TTE learning pathway and how the available educational resources support the learning goals. Section 2.3 is the main content of this chapter which focuses on a variety of learning tools characterised by technological components. As echocardiography is a multidisciplinary field that covers a broad array of knowledge and practical skills, the task of determining a suitable technology used for an individual learning, a lecture class, or a hands-on session has always been a challenge for medical educators. The aim of this section is thus to review the existing literature which address how technology can be integrated into pedagogical designs and strategies in TTE training. In this thesis, web-based multimedia instruction, simulation, and immersive technology—arranged in section lists in chronological order—are selected to study their recent impact upon the efficiency and effectiveness of any transthoracic echocardiography education delivery system. This review also points out to some possible misunderstandings in current use of each technological mediums. For each technological modalities, further details regarding educational benefits—the growth of students' knowledge and technical skills, disadvantages, and potential limitations of using these technologies are also investigated based on the related research work in the existing literature.

2.2 Technology-enhanced transthoracic echocardiography education

Transthoracic echocardiography (TTE) is a non-invasive imaging technique for investigating real-time cardiac morphology and function. After 1990s, TTE was not only used in the field of cardiology but also became part of the important diagnostic procedure of other medical specialties, such as anaesthesia, intensive care, internal medicine, and emergency medicine (Garcia Fernandez, 2014; Beaulieu, 2007; Moore, 2008). The British Society of Echocardiography (BSE)—set correlate with the broad international agreement—has recommended that a thorough understanding of normal cardiac structure and function, fundamental physics of ultrasound and 2D image optimisation is an essential basis of every standard TTE that all echocardiographers should possess (Robinson et al., 2020). There has been significant transformation of echocardiography education during the last decades—from traditional lectures and paper-based textbooks to a utilisation of digital learning technologies. This stems from concerns about limitations in knowledge and skills gained from out-dated learning methods. For example, a standard textbook is a good material for learning theoretical knowledge of basic echo, but it is not the best option for supporting psychomotor skill practice. In this context, it has to be noted that acquiring satisfactory TTE technical skill and competence requires mastery of both manual dexterity and expertise in cognitive interpretation which rely upon a lot of hours of practice with an effective training programme. In addition, several studies pointed out that the shortage of availability of experienced experts (cardiologists or echocardiographers) and volunteer patients affect negatively and significantly the hands-on training in traditional TTE education (Dreyfus, Donal and Pezel, 2020; Labbé et al., 2016). The abovementioned factors are key highlights of the current technology adoption in TTE education. Although the following attempts to present these as individual techniques, the adoption overlap in terms of technological components and instructional possibilities.

2.3 Educational media

2.3.1 Web-based multimedia instruction (WBMI)

Aside from the traditional teacher-led modes of instruction, a recent challenge in echocardiography education is to design learning ecosystems that equip, personalise and self-regulate learning with effective media and materials (Bath-Hextall, Wharrad and Leonardi-

Bee, 2011). Digital media technologies and multimedia instruction have now set the direction of innovative educational approaches (Wipfli, Press and Kuhn, 2013). As mentioned in Chapter 1, recent presentation of multimedia instruction is usually employed in e-learning systems. E-learning is a broad term used to define any use of computers or electronic devices to support education. The integration of multimedia content in e-learning can be utilised by the user to follow a lesson plan for both classroom-setting and/or self-learning activity, with no physical interaction between an instructor and a learner required (Nerlich, 1995; Romaniuk, 2013).

In the recent trend of echocardiography education, web-based multimedia instruction (asynchronous e-learning) is in widespread use for self-directed learning about the fundamental knowledge of echocardiography. It is widely known that many recent echocardiography/cardiology organisations, differing by country or continent, possess their own standards and framework for supporting echocardiography-related clinical practice, research, and education. Although they have a slightly different philosophy, they all apply, as a homogeneous requirement, a body of theoretical TTE knowledge which medical trainees should master. This can be illustrated in Table 2.1. The table compares examples of the essential knowledge in accordance with the principles outlined in the European Association of Cardiovascular Imaging (EACVI) Echo Core Syllabus (Popescu et al., 2009; European Society of Cardiology, 2021) and an e-learning module used for The Focused Intensive Care Echocardiography (FICE) training which was designed by the Intensive Care Society (ICS) in collaboration with the British Society of Echocardiography (BSE) (eIntegrity, 2021).

Table 2.1: Theoretical knowledge for basic, entry-level adult transthoracic echocardiography (TTE) recommended by the EAEVI (left side) and the ICS (right side) (Popescu et al., 2009; European Society of Cardiology, 2021; eIntegrity, 2021)

Core knowledge structures (the EAEVI)	Core knowledge structures (the ICS)
Ultrasound physics and biological effects	Which patients benefit from basic echo?
Principles of echocardiographic image formation and blood flow/tissue velocity	Physics of ultrasound and image optimisation
Machine settings and instrumentation handling for an optimal image quality	Anatomy and basic views
Normal cardiovascular anatomy, including possible normal variants	Left ventricular function
Pathological changes in cardiovascular anatomy in different disease states	Right ventricular function
Normal cardiovascular physiology and fluid dynamics of normal blood flow	Pathology
Pathological changes in blood flow in different disease states	Basic lung ultrasound
Indications, contraindications, and appropriateness criteria	Limitations and pitfalls
Alternative diagnostic techniques for any given situation	
Potential complications (e.g., for Transoesophageal echocardiography (TOE), stress echo, and contrast procedures)	

The mass adoption of web-based multimedia instruction (WBMI) occurs as a starting point of several accreditation schemes including Focused Intensive Care Echocardiography (FICE), Focused Echo in Emergency Life Support (FEEL), and others for higher levels of competence of echocardiography (Price et al., 2008). In general, novice trainees are required to follow the route of training by completing an approved web-based multimedia module, practising hands-on skills, achieving a large number of echo examinations specified in a case logbook, and passing a triggered assessment of echo competency. As presented in the above table, trainees should develop a deeper understanding of the underlying concepts of TTE concerned with ultrasound physics, the echo machine's setting and maintenance, echo image acquisition and diagnostic techniques, normal and abnormal cardiovascular anatomy and function, and should be able to recognise ultrasound artefacts and cardiovascular anatomy that may be misdiagnosed as pathological processes (Popescu et al., 2009). In addition to the programme supplied as part of the echo accreditation approved pathway, medical trainees also have a chance to gain experience with a variety of free or commercial web-based multimedia learning sites. Many of them are produced by the expert team from well-known colleges or universities and hosted on third party commercial platforms (123 sonography, 2021; Association of Anaesthetists,2021).

2.3.2 Educational benefits of web-based multimedia instruction

Educational benefits of web-based multimedia instruction in TTE education have been investigated. Most studies performed to date have focused on the utilization of web-based multimedia programmes as supplementary rather than core teaching/learning resources. This leads to a lack of evidence and consensus regarding the 'actual' effectiveness of the use of web-based multimedia learning modules compared with other educational methods. Many recent published studies relating to the effectiveness of web-based multimedia instruction can be categorised into two types: those evaluating the improvement of knowledge base and cognitive skills of basic TTE examination, and those measuring students' satisfaction after learning with an online multimedia module. In general, it is widely accepted that web-based multimedia instruction is a fashionable tool for constructing knowledge before progressing to the other steps of practical training.

Many experimental studies demonstrated that online multimedia instruction could positively impact on satisfactory performance of interpreting echocardiographic images. For example, Canty et al (2019) present a study which utilised web-based multimedia module in focused cardiac ultrasound (FCU) training for two purposes: theoretical and practical skills improvement. The goal of this study was to investigate whether a multimedia employed in asynchronous online learning course guide for self-directed practice with a TTE simulator could provide educational benefits to novice critical care physicians compared with an existing method—traditional instructor-led training. The analyses performed in this study revealed that trainees achieved satisfactory skills in interpreting TTE images and diagnosing commonly found pathology after learning through online lessons. Moreover, surprisingly, the participants who only experienced with the online multimedia instruction guided self-directed simulator could demonstrate higher scores relating to image acquisition skills than the other group of the traditional learning style supervised TTE practice on role-play patients. These findings reported are in line with other studies which adopted a similar approach of an integration of web-based multimedia instruction module into hands-on or simulator-based training (e.g., Beaulieu et al., 2015; Bernard et al., 2019; Haskins, 2017). Whereas most studies showed a trend to use a multiple-choice question (MCQ) instrument for measuring the development of a knowledge base for image interpretation and image acquisition influenced by online multimedia instruction usage, it is recognised that MCQs assess knowledge rather than skill or performance. Methods of practical skills assessment vary widely depending on the study settings and expert opinion., for example. Assessments mainly involve oral or written reports in which feedback is given verbally rather than via online MCQs. Therefore, computer-based multimedia instruction could not be considered as influencing the improvement of technical skills in basic TTE.

2.3.3 Simulation

Teaching basic TTE skills to novice trainees remains a challenging task. Challenges to date include time and resources constraints, lack of qualified staff, and the high cost of formal education (Kydd et al., 2014). Moreover, Dieden, Carlson and Gudmundsson (2019) found from their qualitative survey that novice trainees addressed their major pain points to practise probe handling and image acquisition skills in TTE education, that is, student preference for echocardiography curriculum is more likely to be associated with the use of educational resources in which improve both technical experience and theoretical knowledge retention. Simulation-based education (SBE) has been accepted as a part of the successful delivery of experiential learning (Nazarnia and Subramaniam, 2016). Thus far, SBE has also been a trend in teaching echocardiography for recent years.

The general concept of simulation is a method or technique for creating an artificial experience without going through the genuine situation (So, Chen, Wong and Chan, 2019). Medical simulation refers to purposely built structures or machines imitating human anatomy, physiology, and movement; or built environment imitating the real clinical scenarios in which medical interventions are administered. The educational goals of medical simulation are to enable the medical trainees to practise specific procedural skills and management of uncommon catastrophic situations through experiential learning activity which does not cause any discomfort or harm to the patient (Al-Elq, 2010; Guze, 2015).

In the design of simulation-based learning experience (SBLE), there are two important keywords to note: modality and fidelity. Modality is the term used to categorise the type of simulation based on technique, equipment and technological innovation. A variety of categories have been recently proposed, for example, the Association of American Medical Colleges (AAMC) stated that there are six modalities of healthcare simulators: (1) Hi-fidelity manikins, robust physiological modelling, and multi-state cases; (2) virtual reality (VR) procedural trainers; (3) virtual patients, 4) task trainers, cadavers and ex-vivo models, 5) Standardised patients (clinical actors), and 6) Blended approaches (Association of American Medical Colleges). There is no one ideal modality of simulation-based learning and the selection of appropriate technique largely depends on many factors including cost, defined learning outcomes, equipment, and technical difficulties (Carey and Rossler, 2021).

The word ‘fidelity’ has become a buzzword in designing SBLE and as such, it is often mistakenly used to referred to simulation modality. However, certain aspects of the definition of fidelity rely on the presence of equipment and materials which has the potential of increasing the sense of realism in learning experience with simulators (Carey and Rossler, 2021). Based on recent studies, simulation can be currently divided into low and high fidelity. Holtschneider (2009) argued that low-fidelity simulator refers to computer- or paper-based tasks which do not provide learners with the immediate feedback and interaction modes, whereas high-fidelity modality often brings the learner into an interactive education experience which mimics realistic clinical problems or scenarios. Meanwhile, Lewiss, Hoffmann, Beaulieu and Phelan (2014) proposed that, although high-fidelity simulators appear to be more effective than low-fidelity simulators at providing trainees the high-tech learning experience, the low-fidelity modalities provide advantages of being easy to use and more affordable compared to advanced instruments.

The development of high-fidelity life-size mannequin simulators is one of the most important and promising technology in TTE education. In recent years. These echocardiographic simulators have become widely used because of an increasing demand for training medical trainees in the field of cardiology, anaesthesiology, intensive care medicine. Conceptually, the high-fidelity simulator system consists of a life-size (torso or full body) mannequin, a high-performance computer combined with advanced graphical and sensor mechanism technologies, and a dummy probe (Clau-Terré et al., 2014)

TTE simulator modules provide opportunities for medical trainees to practice visuospatial perception and psychomotor skills by placing the mock transducer probe over the mannequin surface for performing simulated tasks of echocardiographic image acquisition. Real-time tracking technology has been an important part of medical simulators that is used for determining the position, inclination angles, and orientation of the dummy probe. Among the several tracking technologies applied in medical applications—including inertial tracking (IT), optical tracking (OT) and electromagnetic tracking (EMT), EMT system is highlighted as the most common approach for tracking the probe position in several commercial, and research-based echocardiography simulators. An EMT system is based on an electromagnetic field generator and detectors which allows for detecting motion and position of a mock probe embedded with electromagnetic tracking sensors. EMT has an advantage over other tracking systems in not requiring a direct line-of-sight for detecting the relative position. Moreover, the benefits of EMT come with the slightly smaller sensor size and convenience of use in comparison with other tracking devices (Weidenbach., 1999; Lugez et al., 2015; Chen, Hsieh and Huang, 2017). For cognitive value, the high-fidelity simulator is aimed at enhancing users' knowledge and understanding of echocardiography by providing the useful system based on the integrated use of sensors and feedback mechanisms, and visualisation technology. On the computer screen, 3D realistic representations of the heart—including surrounding organs—and their deformation must be in real-time in order to synchronise with pre-recorded (greyscale) 2D echocardiogram dataset. Motion detection and graphical visualisation follow standard imaging planes and controlled interactively by the user's movements of the mock transducer probe (Nazarnia and Subramaniam, 2016; Dreyfus, Donal and Pezel, 2020).

Figure 2.1: The CAE Vimedix 3.2 representing mannequin-based system simulator for a range of cardiac, lung and abdominal ultrasound procedure: transthoracic and tranoesophageal (TTE/TOE) echocardiography, and transgastric abdominal ultrasonography (TGAUS) (CAE Healthcare, 2021)

Figure 2.2: The HeartWorks simulator representing mannequin-based system simulator for a range of cardiac and lung ultrasound procedure: transthoracic and transoesophageal (TTE/TOE) echocardiography (MedSim Healthcare Education, 2021)

After reviewing the related studies of pedagogical techniques used in TTE education, it is interesting to notice the widespread use of the high-fidelity mannequin-based simulators which were combined in Table 2.2. To date, the most popular commercially available echocardiography simulators used for teaching and training purposes are the Vimedix (CAE Healthcare, Canada) and the Heartworks (Inventive Medical, United Kingdom) (Shakil, Mahmood and Matyal, 2012).

Table 2.2: A list of mannequin-based echocardiographic simulators

	Developer	Utilities	Modalities	Multimedia E-learning	Pathological Scenarios	Commercial Available
Vimedix	CAE Healthcare, Quebec, Canada	TTE, TOE abdominal	2D, colour, M-Mode but no spectral Doppler	Yes	Yes	Yes
HeartWorks	Inventive Medical Ltd, London, UK	TTE, TOE	2D, colour, spectral Doppler	Yes	Yes	Yes
Simbionix	AirPort City, Israel	TTE, TOE	2D, colour and spectral Doppler, advanced hemodynamic calculations	Yes	Yes	Yes
Blue Phantom	Seattle, WA, USA	TTE, TOE	2D only	No	No	Yes
EchoCom	Weidenbach *et al.*, Leipzig, Germany	TTE, TOE	2D only	No	Yes	No
SonoSim	Santa Monica, CA, USA	TTE, TOE, and other ultrasound-guided procedure (e.g., OB-GYN, abdominal)	2D, M-Mode, colour-flow Doppler, continuous-wave Doppler, pulsed-wave Doppler	Yes	Yes	Yes

Abbreviations: TTE = transthoracic echocardiography; TOE = transoesophageal echocardiography; 2D = two-dimensional

Table adapted from Nazarnia and Subramaniam (2016) and SonoSim (2021)

2.3.4 Educational benefits of simulation

With respect to the use of simulation technology to aid transthoracic echocardiography training, the reported occurrence of its effectiveness on students' learning was diverse between different studies ranging from case reports, pilot studies, observations, and prospective randomised studies. This part of the review is presented in a narrative format as the studies identified were of heterogeneous populations and varied in interventions and the data items collected.

The majority of studies reported positive findings in terms of the role of echo simulator which facilitates improvement of learning experience and outcomes. Today, the commercial mannequin-based echocardiography simulators (see Table 2.2) are primarily used for TTE training in most studies. Using a TTE simulator featuring recent advanced technology is important to serve increasing demands for enhancing the efficiency of the TTE curriculum (Matyal et al., 2011; *Clau-Terré et al., 2014; Montealegre-Gallegos et al., 2016).* The common research aim found in the relevant studies is to investigate the usefulness and usability aspects of TTE simulators. Research design can be distilled into comparative study and noncomparative study.

In the comparative study, the comparison often highlights the significant differences between simulation-based training and traditional methods, such as textbooks, articles, online resources (Kusunose et al., 2016), instructional videos, and hands-on demonstrations (Neelanvakil et al., 2012). In the study by Neelanvakil *et al.* (2012), anaesthesia residents in the simulator-based training group achieved better competence than those who were provided with a video tutorial for learning basic TTE knowledge and a hands-on demonstration session for practical skills training. Residents who trained with a simulator could demonstrate significantly higher scores as not only reflecting the ability of identifying the correct anatomical structures within each echocardiogram but also showing better skills in image acquisition than residents trained using traditional methods. However, although simulation-based learning (SBL) method is regarded as a powerful instructional instrument to improve medical trainees’ TTE competency, we cannot conclude that training with a simulator is superior to training with hands-on demonstration on standardised patient or healthy volunteers (Edrich et al., 2014).

To the author's knowledge, the most likely study design that would be found in the literature of TTE education was noncomparative-study. A great demand in recent years for echocardiography training and accreditations in many clinical specialities has affected the increased use of TTE simulator. However, it is a challenge to medical educators to study and find more evidence to support the idea that the use of simulators improves the quality of TTE education (*Clau-Terré et al., 2014).* Therefore, it is valuable for pedagogical reasons for conducting noncomparative studies designed to investigate how TTE simulators should be included in training pathways and how it can complement the existing learning methods.

Several investigators and medical experts observe the use of echocardiographic simulation as an enhancement and accelerator to traditional learning programmes as shown in Table 2.3.

Table 2.3: An overview of the publications' details about the application of echocardiography simulators in TTE Training curriculum

Year Of Publication	**Author (s)**	**Study design**	**Participant characteristics (Number/ Profession**	**M**	**Simulator Modality**
				C	**Conclusion**
2013	Beraud et al.	**Design:** Prospective single-centre study	18 critical care medicine fellows	**M**	Vimedix (CAE Healthcare, Quebec, Canada)
		Knowledge and performance assessment:		**C**	The study proposed the use of simulator test instead of TTE examination on humans after training. Pathological packages of the simulator were used to assess fellows' performance in the

Year Of Publication	Author (s)	Study design	Participant characteristics (Number/ Profession	M / C	Simulator Modality / Conclusion
		Independent examination of image acquisition and interpretation skills		C	interpretation skills, the diagnosis time and scanning time.
2015	Mitchell et al.	**Design:** Prospective single-centre study **Knowledge assessment:** Written test **TTE performance assessment:** TTE examination on human models	6 anaesthesia interns	M	Phantom models (Blue Phantom, Sarasota, FL, USA), homemade models, HeartWorks (Inventive Medical Ltd, London, UK), and VIMEDIX (CAE Healthcare, Quebec, Canada)
				C	The study did not focus solely on specific value of the use of simulation. Successful results in increased knowledge and manual skills of trainees are caused by attending a multimodal course which covers a range of educational techniques including instructional videos, internet- and simulation-based teaching.
2016	Montealegre-Gallegos et al.	**Design:** Prospective single-centre study **Knowledge assessment:** Pre- and post-tests	16 cardiology fellows	M	Heartworks (Inventive Medical, London, England), and Vimedix (CAE Healthcare, Quebec, Canada)
				C	In TTE education context, it is easier to teach and assess the improvement of knowledge rather than procedural skills. The utilisation of TTE simulator plays a great role in promoting a more

Year Of Publication	Author (s)	Study design	Participant characteristics (Number/ Profession	M / C	Simulator Modality / Conclusion
		TTE performance assessment: TTE examination on humans		C	efficient psychomotor training as well as can be an effective tool to be used in assessing manual skills in medical trainees.
2016	Skinner, Freeman and Sheehan	**Design:** Prospective single-centre study **Knowledge and performance assessment:** Pre- and post-tests of multiple-choice question based on clinical cases	22 residents from internal medicine, family medicine, surgery, anaesthesiology training.	**M**	Homemade simulator
				C	Self-paced learning with simulator is an effective strategy for training TTE image acquisition and optimisation skills. Simulator-based training provides the opportunity for trainees to practice hand-eye coordination skills without any assistance by experts or tutors.
2016	Townsend, Kendall, Barnett and Robinson	**Design:** Prospective single-centre study **Knowledge and performance assessment:** An OSCE (objective structured clinical examination) comprising image acquisition and image interpretation scoresheet	20 surgical residents	**M**	SonoSim (Santa Monica, CA, USA)
				C	Simulation-based learning is well integrated with didactic lectures following the OSCE design for training and assessment for focused assessment diagnostic echocardiography (FADE) examination.

Year Of Publication	Author (s)	Study design	Participant characteristics (Number/ Profession	M / C	Simulator Modality / Conclusion
2018	Dayton, Groves, Glickstein and Flynn,	**Design:** Prospective single-centre study **Knowledge assessment:** pre- and post-tests of multiple-choice question **TTE performance assessment:** pre- and post-tests of open-ended questions based on different cases of coronary heart disease (CHD)	11 paediatric cardiology fellows	**M**	EchoCom (Leipzig, Germany)
				C	Realistic representation of simulator well benefits paediatric cardiology trainees in an improvement in their knowledge of CHD and echocardiographic performance.
2018	Vignon et al.	**Design:** prospective bi-centre study **Knowledge assessment:** pre- and post-tests of multiple-choice question **TTE performance assessment:** pre- and post-tests of open-ended questions based on different cases of coronary heart disease (CHD)	24 non-cardiologist residents	**M**	Vimedix (CAE Healthcare, Quebec, Canada)
				C	Recent technological advances in computerised simulation on mannequin has proved to reduce the learning curve and improve technical and practical skills in novice residents who have no prior experience of TTE. Residents in simulation-based training group can show significant improvement of their TTE competency rather than residents in conventional-based methods.

Year Of Publication	Author (s)	Study design	Participant characteristics (Number/ Profession	M / C	Simulator Modality / Conclusion
2018	Winter, Lindqvist and Sheehan	**Design:** Prospective single-centre study **Knowledge assessment:** N/A **TTE performance assessment:** TTE examination on simulators aimed at testing image acquisition skills	61 (37 physicians, 22 sonographers and two nurses)	M	Homemade simulator developed at the University of Washington
				C	In many present studies, psychomotor skill of trainees is qualitatively assessed and based on expert judgement. The authors proposed a quantitative method of assessment by using a TTE simulator for measuring technical skill in terms of the deviation angle between an acquired image and the anatomically correct plane for each TTE views.
2019	Bernard et al.	**Design:** Prospective single-centre study **Knowledge assessment:** pre- and post-tests of multiple-choice question **Psychomotor skill assessment:** TTE examination on humans	35 trainees in cardiology, emergency medicine or anaesthesiology	M	HeartWorks (Inventive Medical Ltd, London, UK),
				C	A blended learning curriculum using online learning resources, self-learning simulation and practical workshop (using real patients) successfully accelerates TTE knowledge and practical skill construction in novices in echocardiography.

Year Of Publication	Author (s)	Study design	Participant characteristics (Number/ Profession	M / C	Simulator Modality / Conclusion
2019	Canty et al.	**Design:** Prospective single-centre study **Knowledge assessment:** Pre- and post-tests of multiple-choice question **Psychomotor skill assessment:** TTE examination on humans	145 novice critical care physicians	**M**	Vimedix (CAE Healthcare, Quebec, Canada)
				C	Self-direct learning with simulator may be an alternative to conventional hands-on training on live models.
2019	Sheehan, McConnaughey, Freeman and Zierler	**Design:** Prospective single-centre study **Knowledge assessment:** N/A **Psychomotor skill assessment:** TTE examination on simulators	22 residents in internal medicine, family medicine, anaesthesiology , or surgery	**M**	Homemade simulator
				C	Innovative technology of visual and quantitative feedback of TTE simulator benefits residents in developing visuo-spatial ability during their practice. The feedback provides a quick and easy guide for optimising echocardiographic images which is important to help residents achieve their proficiency as well as facilitate the transfer to real clinical practice. .

In summary, utilisation and potential benefits of simulation in TTE education are numerous and differ based on several forms of practice and desired learning outcomes. Some studies were aimed to use the features of recent available commercial echocardiographic simulators integrated into the existing teaching curricula with the goal of bringing about meaningful student learning, filling the gap in availability of experts and facilities, and shortening the study time. On the other hand, some studies were driven by a concern about non-standardised methods for psychomotor skills tests, which are qualitative, and often based on expert judgments. This challenge led to the development of feedback control systems integrated into the echocardiographic simulator which was designed to evaluate learners' image acquisition skills quantitatively.

2.3.5 Immersive technology

The idea of utilising immersive technology—including virtual reality (VR), augmented reality (AR), and mixed reality (MR), into cardiovascular medicine and surgery has been popular. Compared with conventional training techniques or standard approaches for the treatment of cardiovascular conditions, immersive technology provides several greater benefits which have been identified in various studies, for example, promising new methods to visualise three-dimensional anatomical structures for preoperative planning purposes (Brun et al., 2018; Sadeghi, Taverne, Bogers and Mahtab, 2020), allowing surgeons to step into and interact with patient-individualised reconstructed 3D images which are represented in a virtual reality (VR) simulation in surgical planning for video-assisted thoracoscopic surgery (VATS) (Frajhof et al., 2018; Ujiie et al., 2021).

Through focusing on the feasibility of using AR, VR and MR in echocardiography context, it is noticeable that many recent studies are conducted for supporting clinical approaches rather than educational purposes. The initial idea behind these research works is an underlying limitation of the representation of 2D or 3D echocardiography images which are normally represented on flat 2D monitors. It could impede the ability of doctors to visualise the complicated heart structures and conditions to make an accurate diagnosis. Therefore, there have been attempts to adopt AR, VR or MR techniques and investigate whether these applications can help users better understand echocardiography images and have the potential to become useful clinical tools. For example, a study by van den Bosch et al. in 2005 and a study by Kasprzak et al. in 2019 demonstrated the use of real-time holographic mixed reality which projected 3D transoesophageal echocardiography data from patients with mitral valve conditions onto the physical environment. The MR technology allows the operators to view the holographic image from different angles, as well as interact with and control it by hand gestures. Implementation of interactive hologram experiences enable the cardiothoracic surgeons to assess the preprocedural anatomy/pathology and function of mitral valves quickly and precisely and know their exact location for optimising balloon position across the mitral valve leaflets. (van den Bosch et al., 2005; Kasprzak et al., 2019).

To the best of the author's knowledge, there is a lack of existing evidence in the emerging area of using immersive technology for basic transthoracic echocardiography education. There was only one study conducted by Weidenbach and his colleagues with regard to training of echocardiography based on the term of augmented reality interface. However, it was just a preliminary study, outdated, and had several limitations, for example, the AR simulator used in the study did not fit with the actual concept of augmented reality—

in which digital graphics must be directly overlaid on top of a physical world that a person can already see—as users could only interact with a transducer dummy by manipulating it on a plastic torso model and seeing graphical representations of 3D hearts and the registered 3D echocardiographic images shown on a desktop computer screen (Weidenbach et al., 2000). To date, although commercial AR training systems for echocardiography education, e.g., CAE VimedixAR, have proliferated (Diagnostic and Interventional Cardiology, 2019), their educational effectiveness and impact on students' learning experience and outcomes in echocardiography training have not been sufficiently studied.

2.4 Discussion

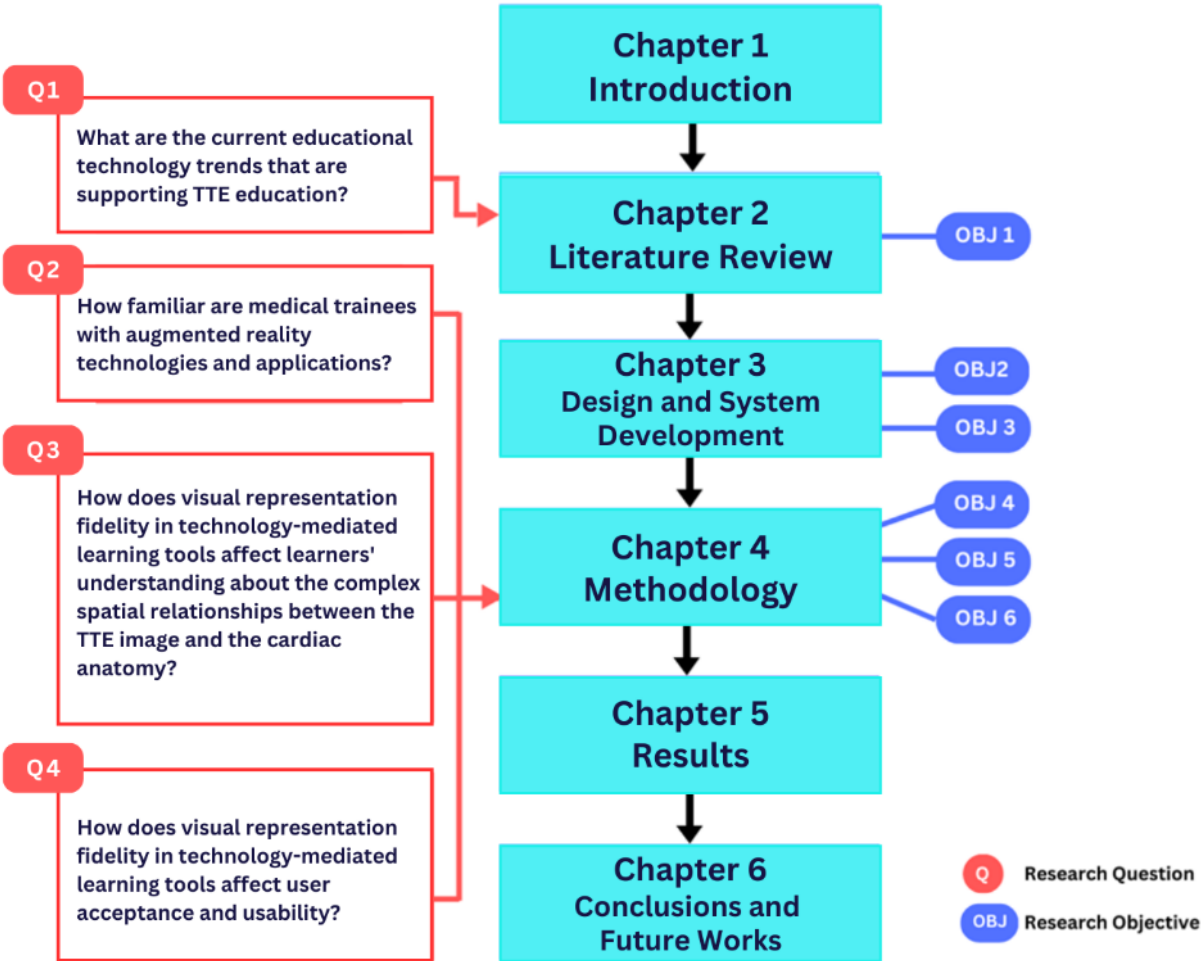


Figure 2.3: *Thesis roadmap – Chapter 2*

According to the thesis roadmap in Fig. 2.3, the objective of this review is to determine how the trend of digital technology can be adopted for supporting TTE education. In the context of this research, the review focuses on each of the three emerging technological modalities: web-based multimedia instruction, simulation, immersive technology. The definition, availability, and trend of application of each tool are described, and summaries of the educational benefits of selected tools are provided.

Web-based multimedia instruction is addressed in the first section as it should be treated as a starting point in introducing innovative technological tools which can be an impactful adjunct to traditional methods that currently exist in the halls of medical education. As opposed to just learning with a completely passive lecture or demonstration in a classroom, a new generation of learners is benefitting from a variety of multimedia resources offering them a personalised learning opportunity for a more self-directed and self-paced learning experience. Some of the most common methods of utilising computer-based multimedia instruction for TTE education have been discussed in this chapter (*Popescu et al., 2009; European Society of Cardiology, 2021; eIntegrity, 2021).* Despite a wide range of studies about the use of computer-based (web-based) multimedia learning modules in different pedagogical designs for TTE education, for example, an online multimedia learning course followed by a hands-on session or training on simulation mannequins, no such formal experimentation exists on how web-based multimedia instruction itself impacts on students' knowledge level and personal preferences.

The second section of this chapter initially addresses the possible misconception that can occlude understanding of each type of simulation tools in medical education. It is critical for educators, or medical instructors, to realise the importance and be able to differentiate between two keywords: modality and fidelity. Modality is a reference to the medium used to deliver a simulation-based learning (SBL) that is further described in detail based on the selected examples (Chiniara et al., 2012; The Group on Information Resources, Simulation in Academic Medicine Special Interest Group*, 2014),* whereas fidelity is a reference to the degree of realism portrayed in a simulated learning experience. With the description in Chapter 1, delivering echocardiography training requires a strong focus on the implementation of theoretical knowledge into the required psychomotor development, this could lead to increasing use of high-fidelity life-size mannequin simulator as it becomes indispensable as an alternative to hands-on TTE training with real-life patients or healthy human models (Brown and Tortorella, 2020). The use of high-fidelity echo simulator, especially the commercially available models, is evidently more popular, although more expensive, than a low-fidelity (tabletop) simulation. Overall, much research evidence shows that a high-fidelity life-size mannequin simulator can offer a much greater impact on medical trainees' achievement and preference than learning with traditional mediums, and also be an effective instructional tool for a hybrid TTE training mode—combining traditional lectures, video or online tutorials, and TTE practice session with live volunteers or simulators.

Innovations in immersive technology and its potential benefits in TTE education are focussed in the third section. AR, VR and MR—the most common mentioned techniques under the umbrella of immersive technology — are relatively little used in TTE education, although its acceptance has been increasing in the healthcare arena. Given examples are described and show that the holographic AR technologies, including MR which is an enhanced version of AR, have been the popular technique used for enhancing medical trainees' level of understanding of the complicated heart structures and ability to apply their knowledge learnt to real-life clinical treatment. However, no study has to date investigated the direct impact of such benefits of AR within the context of basic TTE education.

2.5 Conclusion

Overall, the literature review provides some evidence to support and discuss the direction of technology movements and innovation of educational tools for supporting basic transthoracic echocardiography (TTE) education. Whereas computer-based (online) multimedia instruction and simulators are two supporting materials which are popular and frequently used in recent TTE education and training, the use of AR applications is scarcely found in the literature. Moreover, no studies in TTE education investigating the effectiveness of visual presentation in multimedia learning methods on students' cognitive performance and their satisfaction have been reported in the literature thus far. These mentioned reasons are highlighted and thoroughly explored in this thesis which will be explained in the next chapters.

Chapter 3

Design and System Development

3.1 Introduction

As earlier mentioned, the investigation of effectiveness of educational media technologies for supporting participant engagement with the basic TTE knowledge is the goal of the study. This chapter will detail how theoretical design, software components, and hardware modules are integrated to achieve desired features and functionalities of a marker-based augmented reality (AR) system and a computer-based multimedia learning module that are made for self-directed learning experience.

At an early stage of the research development, the author was recommended by subject matter expert (SME) of the Institute of Cardiovascular Sciences, University Hospitals Birmingham, to do some observational research or attend an echocardiography training workshop which might be helpful to provide ideas for designing and developing educational media which continue to be investigated. Therefore, the author decided to attend an approved basic echo workshop organised by the Intensive Care Society (ICS) and British Society of Echocardiography (BSE). As well as providing the author with basic TTE knowledge and skills, it also provided a great opportunity to meet the real novice trainees and observe their behaviour in the workshop-based learning environment. Details of this observational approach are provided in Section 3.2.

Section 3.3 demonstrates the application of human computer interaction (HCI) and human-centred design (HCD) for developing the user interfaces (UI) and the user experience (UX) of two learning media prototypes—an augmented reality application and a computer-based multimedia instruction learning—which are employed for the study intervention.

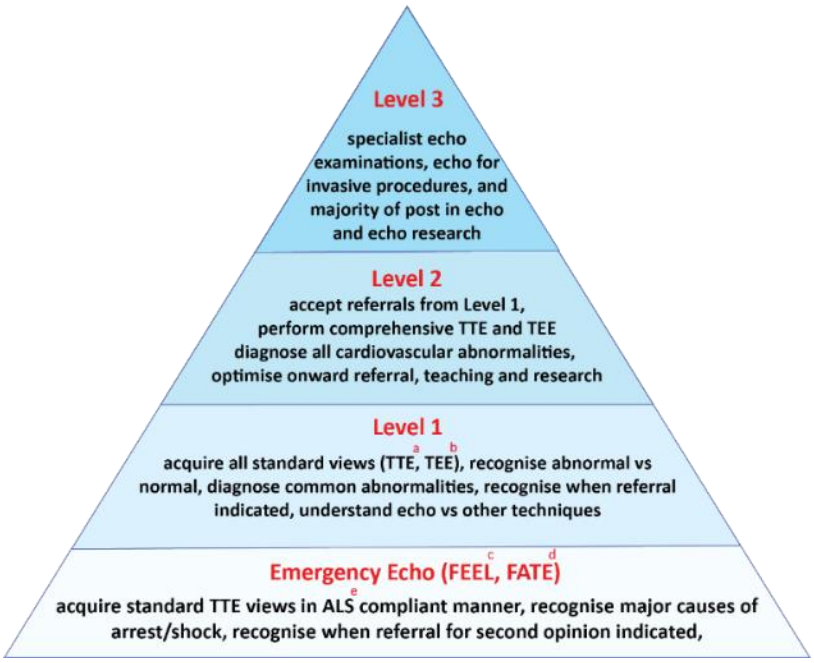
Section 3.4 outlines the creation of interactive 3D cardiac anatomical models which are consolidated into the systems for computer-based multimedia instruction and AR applications. These 3D graphics are designed and developed from scratch instead of using existing 3D anatomical models on the market, because current commercially available 3D models cannot match the quality requirements for visualising anatomical structures regarding four basic TTE windows—parasternal long axis (PLAX), parasternal short axis (PSAX), apical 4 chamber (A4C), and subcostal 4 chamber (S4C). Software and techniques used in the 3D production pipeline are also described.

Section 3.5 and section 3.6 explains the system configuration and the development process of the two main types of educational media to be investigated—the computer-based multimedia instruction and the marker-based augmented reality applications.

Section 3.7 summarises the framework how the developed learning resources are employed in the case study.

3.2 Content preparation

In order to narrow the few subtopics that are of greater specificity and detail about the utilisation of technological resources in echocardiography education, it is critical to understand the characteristic of the course or pathways commonly proposed for echocardiography training in United Kingdom, and how learning resources have become valuable adjuncts to formal TTE training. According to a summary of standards for accreditation provided by the British Society of Echocardiography (BSE) Departmental Accreditation Committee (Ritzmann, et al., 2020), there are various standards of accreditation provided for the practice of medical personnel. In general, standards are arranged to cover all levels of competence of echocardiography practice, including transthoracic echocardiography (level2), transoesophageal echocardiography, stress echocardiography, as well as intensive care and emergency echocardiography. Levels of accreditation are displayed in more details in Figure 3.1 (Price et al., 2008).



[a] TTE = Transthoracic Echocardiography

[b] TOE = Transoesophageal Echocardiography

[c] FEEL = Focused Echocardiographic Evaluation in Life Support

[d] FATE = Focused Assessment with Transthoracic Echocardiography

[e] ALS = Advanced Life Support

Figure 3.1: Pyramid diagram of levels of competence in echocardiography and ultrasound practice (modified from Price et al., 2008)

After reviewing the British Society of Echocardiography Departmental Accreditation Standards 2019 (BSE DA Standards 2019) (Ritzmann, et al., 2020) and discussing with the subject matter expert, it was decided that the scope of this thesis should be focussed on a first very basic step of competence of echocardiography. In the UK, there are two most mentioned accreditations provided for training in emergency echo—an entry level of competence lower than Level 1 BSE—called Focused Echocardiographic Evaluation in Life Support (FEEL), and another alternative is Focused Intensive Care Echocardiography (FICE).

Although review of published literature as well as the BSE standard document provided preliminary ideas of knowledge, practice, and the use of technology in echocardiography education, there was a need for more details about actual TTE training environments, students tasks and their behaviour which will be useful for further investigation of the design and development process of educational materials. Therefore, the author was advised to attend the FICE course module 1 and 2 to shadow the actual experience of echocardiography training and the role between medical trainees and instructors.

3.2.1 Preliminary research step: completion of Phase 1 of FICE module

3.2.1.1 FICE course overview

FICE accreditation is a training pathway for transthoracic critical care echocardiography which is run by the collaboration between the British Society of Echocardiography (BSE) and The Intensive Care Society (ICS). The course is aimed at intensive care unit clinicians who want to achieve echocardiography accreditation. The FICE course consists of three phases as shown in Table 3.1.

Table 3.1: FICE accreditation pathway

Phase	Modules	Role	Source/Detail
1	Self-direct learning via online earning module	Trainee	http://www.e-lfh.org.uk/programmes/icu-echoultrasound/ *(1-year license)*
	Attend a pre-approved course of basic echocardiography	Trainee	A list of approved courses are available on the Intensive Care Society website
2	Complete a logbook of 50 echo exams (10 scans under directly supervision by mentor)	Trainee	Within 1 year from the 1st to last scan
	Take a triggered assessment	Trainee (Administered by Supervisor +/- mentor)	
3	Complete sign-off sheet sent to ICS secretariat	Supervisor +/- mentor	
	Candidate receive a certificate award for successful completion	The Intensive Care Society	

3.2.1.2 Online learning platform

According to the Focused Intensive Care Echocardiography (FICE) accreditation pack (Intensive Care Society, 2021), clinical personnel who plan to achieve the accreditation should complete an interactive web-based learning course before attending a hands-on workshop. The Intensive Care Echo and Basic Lung Ultrasound (ICE-BLU) interactive online course imparts the core concepts of intensive care echo and lung ultrasound. The user interface of the web-based multimedia learning module is designed to be user-friendly, and incorporates features such as a menu button, backward and forward buttons, an easy-to-read text font, a set of formative quizzes, and video tutorials (see an example in Figure 3.2). The module also provides a variety of images and videos of real echocardiogram and echo test demonstration. The online multimedia learning contents cover nine parts as follow:

- Which patients benefit from basic echo?
- Physics of ultrasound and image optimisation
- Anatomy and basic views
- Left ventricular function
- Right ventricular function
- Pathology
- Basic lung ultrasound
- Limitation and pitfalls
- 25 multiple-choice questions for self-assessment

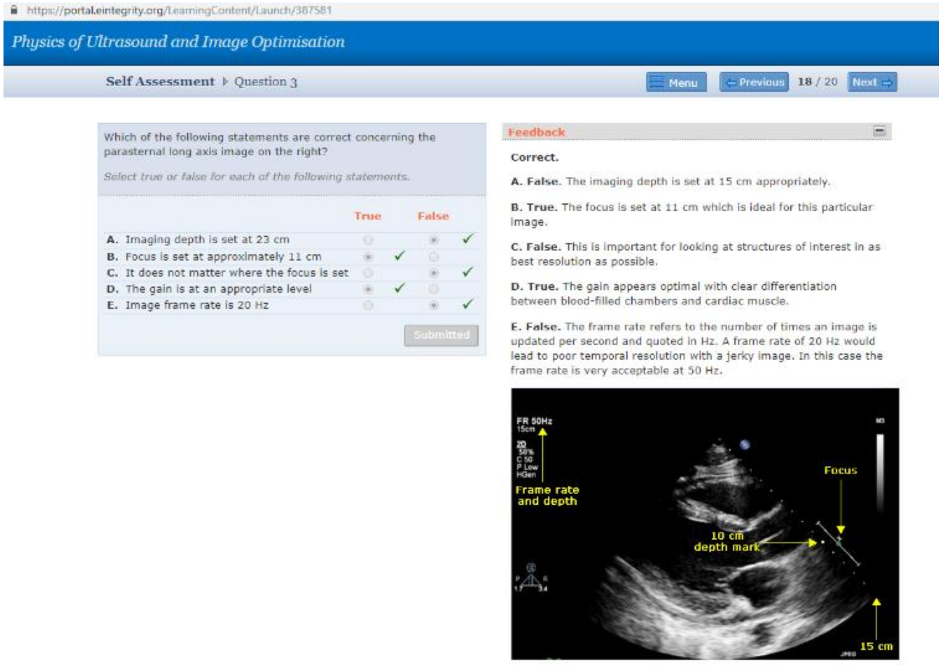


Figure 3.2 An example of ICE-BLU eIntegrity module interface (eIntegrity, 2020)

3.2.1.3 One-day hands-on training workshop

The ICS announces a list of hands-on training workshops annually on its website. The courses vary in locations and administrators around the UK. One-day training offers two main sessions—lecture and hands-on practice.

<u>Pre-Course</u>

The course administrator emailed a set of documents to participant—FICE accreditation pack, a venue map, and course syllabus.

<u>Post-Course</u>

The participant would get the course certificate via email. The participant who aims to complete next processes of FICE accreditation can register online through the ICS website.

Programme

Table 3.2: FICE 1-day training programme information

Section	Duration (min)	Details
1	15	Introduction to the course and syllabus
2	45	Basic physics, ultrasound machine demonstration, knobology, image acquisition and optimisation
3	45	Sonoanatomy, basic echo views, measurements – demonstration
4	45	Common pathologies, interesting cases
5	15	FICE Accreditation process
6	75	Hands-on session 1
7	60	Hands-on session 2
8	60	Hands-on session 3
9	15	Discussion

(Lists exclude coffee and lunch break)

Lecture session

Lecture session was well matched to the web-based learning module (ICE-BLU) context. The classroom projector was synchronised with an echocardiograph machine showing the real-time echo examination on a volunteer subject. Aside from the core concept of intensive care TTE, the instructor team shared their experience, discussed commonly found pathologies, and provided more details about the FICE accreditation and registration process to participants. For more clarification, the environment of lecture session was illustrated by the author as shown in Figure 3.3.

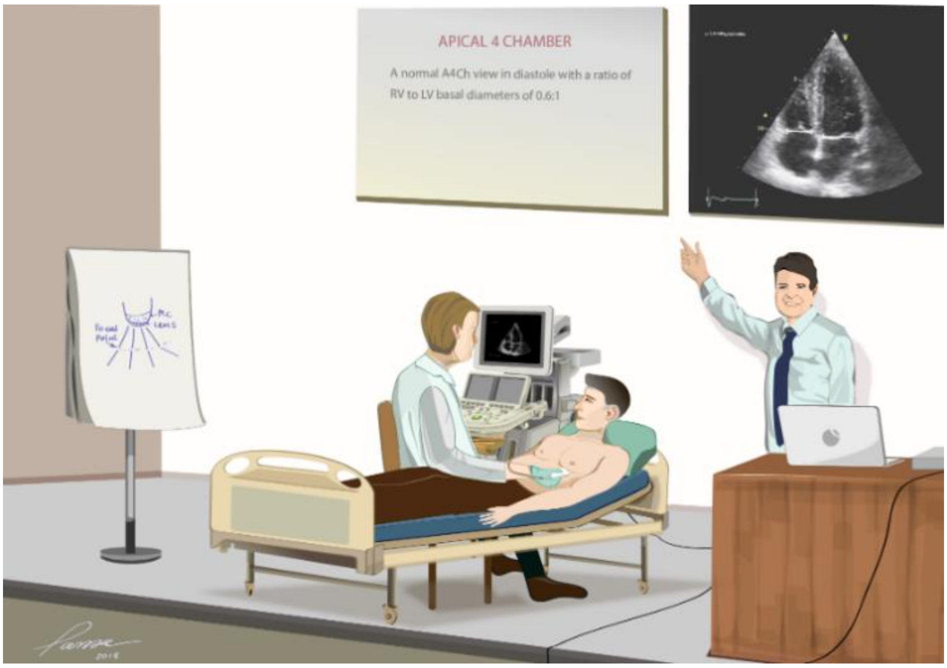


Figure 3.3 Environment of the lecture section

(Original illustration created by the author, Pansa Noiskul)

Echo image reference (eIntegrity, 2021)

Hands-on workshop

All participants were allocated into a small group (3-4 persons per group). Total six groups (group A, B, C, D, E, F) were provided with three consecutive hands-on stations, more details are shown in Table 3.3. The environment of hands-on session was illustrated by the author aiming to clarify and capture the concept of simulator-based training for practising basic TTE examination as shown in Figure 3.4.

Table 3.3 FICE hands-on section tasks

Learning objectives for hands-on sessions
1. Total 6 groups A to F 2. Each group does three consecutive stations (sessions 1,2 and 3) 3. Each group spends 75+60+60=195 minutes on hands-on sessions (total 3 sessions) 4. Each participant spends approximately 15 min hands-on practice in each session 5. When participant is not scanning, he/she will observe and learn from other colleagues 6. Ranges of 6 Phillips machines are available
General set up
1. Connect the US system to power socket 2. Switch ON/OFF button 3. Enter patient demographics 4. Connect US transducer to machine, connect ECG cable to patient 5. Choose US transducer, Orientation of US probe (left/right) 6. Screen/ keyboard/ image up/down and freeze/unfreeze
Optimising the US image
1. Gain 2. Depth (observe change in frame rate) 3. Sector angle (observe change in frame rate) 4. Time Gain Compensation (TGC)
Emphasize
1. Patient position 2. What is the starting position? 3. How should the probe be held? 4. Where should the orientation marker of the probe be aimed? 5. Adjust and optimise the image
Views to be obtained
For FICE 2D only, if time allows/ advanced participant use Colour Doppler, Pulse Wave Doppler, Continuous Wave Doppler 1. Parasternal long axis 2. Parasternal short axis 3. Apical 4 chamber 4. Subcostal 5. Inferior vena cava 6. Right pleura (vertical position of probe in the mid-axillary line) 7. Left pleura (vertical position of probe in the mid-axillary line)

Figure 3.4 Environment of the hands-on training section

(Original illustration created by the author, Pansa Noiskul)

Echo image reference: ICE-BLU web-based learning module

3.2.1.4 Discussion

Lecture session

The instructors rotated through different topics. They also shared their clinical experience and iterated some practical techniques which are not mentioned in the ICE-BLU web-based learning module such as image optimisation technique in ICU and understanding in patient’s mechanics of breathing during the echo test.

Hands-on workshop

During the hands-on workshop, tutors and volunteers (role-play patients) were allocated into 3 groups. The expert teaching team came from various backgrounds such as advanced critical care practitioners (ACCP), ICU specialist registrars (SpR), and cardiac anaesthesiologists. The workshop started with echocardiographic demonstration from the experts in obtaining 7 basic echo views (parasternal long axis, parasternal short axis, apical 4 chamber, subcostal, inferior vena cava (IVC), right pleura and left pleura). After demonstrations, the trainees would be allowed to practis e echo examination. Each member rotated after he/she already achieved 7 echo standard views.

Obtaining qualified echo images depends on the trainee’s personal background. Regarding the observation of group members, a senior anaesthesiologist could attain qualified echo practice faster than other members (two med students and the researcher). Additionally, the anatomy of a volunteer subject has effects on image optimisation. For example, it was easier to perform echo test on a normal-size male volunteer than an overweight female volunteer.

After completing three hands-on sessions, attendees and the lead instructor were recalled from the workshop stations to the lecture room for a last discussion. A series of 10 multiple-choice questions on echocardiograms in various pathologies were discussed for 20 minutes.

3.2.1.5 The analysis of gaps and limitations

There are two disadvantages of online multimedia learning modules that may have an impact on student engagement: time access restriction and lack of interactivity in user interface (UI). The license of ICE-BLU online learning module allows a user to access for only one year. If this were given for longer access permission, it would help trainees to update their knowledge and support their lifelong learning in TTE. The interface design of the ICE-BLU learning module is good for contextualised learning, but it does not provide much visualisation and interactivity. It is crucial that clinicians can visualise the relationship of heart anatomy and echo images in their mind during TTE examination. The current interface of ICE-BLU represents only two-dimensional (2D) images and videos with associated text. Compared with other current web-based learning applications, the ICE-BLU platform should improve users' digital experience. For example, users should be able to actively interact with a three-dimensional (3D) model of the heart in sync with the real echocardiogram on the screen. The clear and precise heart models can help users read the echo image.

Regarding the one-day training course, use of the role-play patients in hands-on training benefits trainees by helping to improve image acquisition skills. However, healthy volunteers cannot support them to learn about commonly found pathologies in TTE. During the hands-on session, trainees rotated through three stations to practise TTE on different volunteer subjects, but there was no significant difference among the stations—repetition of scanning 7 basic echo views. Due to this limitation, it can cause trainees to lose their attention to the training. It was observed that only 1/3 of the trainees had stayed until the course was done.

3.3 Instructional design of interactive learning systems based on the human computer interaction (HCI) and the human-centred design (HCD) fundamentals

The author initiated the study by reviewing related literature on the trend of digital technology adoption for supporting TTE education and completing the Phase 1 of the Focused Intensive Care Echocardiography (FICE) module—constructing background TTE knowledge with self-directed web-based learning module and attending an approved basic echo workshop listed on the Intensive Care Society website—for answering the Research Question 1 ***'What are the current educational technology trends that are supporting TTE education?'*** Findings from the literature review indicated that understanding the spatial relations between cardiac anatomical structures and transthoracic echocardiographic planes (windows) is the first challenge of medical trainees for priming themselves before practising echocardiography examination. In recent years, with the development of computer technologies, it has become much easier for educators to apply educational media tools in their class for supporting their students to construct knowledge—both conceptual (facts or 'what' information) and procedural knowledge ('how' and 'why' information)—about echocardiography. Primarily, medical trainees learn from textbooks or traditional lectures and often struggle with the process of applying their knowledge to actual echocardiography tasks. Therefore, educational learning tools such web-based multimedia instruction (WBMI) and echocardiographic simulators have played an important role in modern echo education. Web-based multimedia instruction is addressed as it should be treated as a starting point for introducing innovative technological tools which can be an impactful adjunct to traditional methods, whereas simulation has been widely adopted in echo training as it provides various benefits for improving manual dexterity in echo practice. The author also pointed at immersive technology—an umbrella term encompassing virtual reality (VR) and augmented reality (AR)—

as it has brought exciting opportunities for medical education. However, such evidence regarding the use of VR or AR for basic TTE education is rare in literature.

Further discussions with clinical supervisors from the Queen Elizabeth Hospital Birmingham (QEHB) contributed to conceptualising the idea of the study. They shared their thoughts and experiences about recent echocardiography training and its role in clinical use. It was generally agreed that TTE has recently become an important procedure in bedside diagnosis in managing patients with cardiac disease or critically ill patients. This causes an increasing demand among medical personnel for achieving accreditation of echocardiography skills (Kydd et al., 2014). The QEHB experts also highlighted the benefit of innovative educational tools in improving quality of echocardiography education. Web-based multimedia learning modules and echocardiography simulators appear to be often used as an approach to support medical trainees to be engaged in learning TTE. This viewpoint is in accordance with the popular trend of integrating educational tools into recent echocardiography training—as stated in Chapter Two. The experts also suggested the need to consider other forms of educational media for TTE education. They located an area of interest in immersive technology, AR or VR, as it has become a new wave of technology currently upgrading medical education. As mentioned in Chapter 2, the existing literature has provided scarce concrete evidence regarding the utilisation of AR and VR in TTE education, and this became a central challenge of this PhD study on how to determine a proper methodology to develop and investigate the impact of implementing the immersive tech as a learning tool for TTE education. Kydd et al. (2014) and Dieden, Carlson and Gudmundsson (2019) addressed research interest in problems and challenges about echocardiography education. Their studies stated that mastering in echocardiography knowledge and skill requires an extensive training regime. In general, physician trainees need to go through a lot of tasks in order to achieve great academic success or an accreditation in echocardiography—tailoring their own study scheme of grounding knowledge of echo, applying for the approved training workshop for experiential education (lecture-based and hands-on sessions), completing an echocardiography logbook, and passing formative and summative assessments. These requirements are not feasible—according to medical trainees' reflection—and should be transformed to create a better education system. Many challenges were addressed in the literature such as the limited number of senior staff members or echo experts who are available for supervision, failure to progress in echo training within required time scale for receiving an echo accreditation, etc.

According to the study executed by Kydd et al. (2014)—which highlighted the feedback received from specialty trainees years 3 to 7 (ST3 to ST7) who joined the meeting held by the British Society of Echocardiography (BSE) and British Junior Cardiologists' Association (BJCA), and a few surveys executed by the General Medical Council (GMC) during 2012 – 2013; there was a persisting imbalance between the trainees' needs and availability of staff and resources for simulation-based training provided at their local hospital/echo lab. Current technology of simulators has become an integral component of modern training in core echocardiography skills. Educators in training programmes generally utilise the high-fidelity mannequin-based echo simulator to facilitate psychomotor skill acquisition in medical trainees. A simulator-based workshop is generally incorporated with a core knowledge lecture session. There exist currently many commercial solutions of echocardiography simulators for educative purposes, HeartWorks is the most popular in the UK (Shakil, Mahmood and Matyal, 2012). Although it has been proven that these simulators are a great solution for enhancing in trainees an understanding of the three-dimensional (3D) orientation of the heart along with developing technical competence (manual dexterity) in performing echocardiography examinations, most of them are high-priced. The cost of these simulators may make it inaccessible in many resource-limited locations. Furthermore, the utilisation of echo simulator is only effective when carried out under the supervision of experts during the hands-on sessions. Medical trainees, hence, reflected their feedback in the abovementioned surveys regarding a lack of access to getting experience with the simulators.

Abovementioned factors therefore led this PhD study to focus on innovative ways to increase the availability of learning opportunities for medical trainees who are novice in transthoracic echocardiography. Some clinical supervisors at the QEHB addressed a positive thought about self-paced learning experiences. As a lack of available accredited echo experts/clinical tutors and heavy workload of most physicians remain challenging in bridging the ideal curriculum and the operational curriculum, technology enhanced self-paced learning could be a potentially interesting solution.

The author initially settled on the idea of development and use of immersive technology —augmented reality (AR)—as a novel media tool for TTE education. The specific area of interest is the impact of 3D graphics presentation of augmented reality (AR) on learners' knowledge improvement and their satisfaction. In this thesis, visual presentation in the proposed AR application refers to a combination of data-driven 3D anatomical animations along with real echocardiogram footage and virtual information that are overlaid onto a torso mannequin. This allows for creating virtual environments where learners can visually engage with representations of the data for simulating actual probe orientation in transthoracic echocardiography (TTE) examination.

There was no concrete evidence in literature stating the implementation of AR technology for self-paced TTE learning. This is probably due to the fact that the majority of medical trainees are not familiar with this technology in their self-learning mode. For determining how learning outcomes are due to the self-paced learning with AR application as opposed to being due to some other learning method, it was hence crucial to select another educational tool as a benchmark for comparison. Accordingly, the author paid attention to asynchronous computer-based multimedia instruction as another learning media tool which would be utilised in the research study. Computer-based multimedia instruction has entered the prolonged widespread use in medical education with which most recent students are familiar; it also best serves the purpose of self-paced learning. According to the cognitive theory of multimedia learning (CTML) by Mayer (2014), visual presentation in multimedia environment refers to any type of media which can be seen by the human eyes, such as photographs, maps, infographics, illustrations, videos, or animations. In this thesis, visual presentation in the proposed multimedia instruction refers to a combination of 3D anatomical animations along with real echocardiogram footage and virtual information that are similar as those in the AR application, but the learners can only experience with interactive 3D learning modules in the computer screen.

For developing the interactive learning systems used in this research, the human computer interaction (HCI) is used in conjunction with the human-centred design (HCD) as the developmental framework, as depicted in Figure 1.1, Chapter 1. Throughout the literature review, meetings with subject matter experts, and attending the first phase of the Focused Intensive Care Echocardiography training, the author was able to define the clear description of the learning media's context of use, an understanding of the needs of the user groups, their characteristics in relation to learning media use and the tasks the learning media is required to assist with, in order to achieve pre-defined goals. The assumptions related to the learning media design based on HCI and HCD are summarised in table 3.4.

Table 3.4: The alignment of HCI and HCD factors to the learning media design

HCI factors	HCD factors	Reflection from the literature review, discussion with experts, and attending the first phase of the FICE course
Use and context	Understanding and specify the context of use	• **Current learning pain points in basic TTE:** novice trainees have difficulties achieving a conceptual understanding of spatial relationships between the echocardiography image and the complicated cardiac anatomical structures • Medical educators/ professionals have become interested in the possibilities of using interactive 3D digital learning media to increase their students' engagement and motivation
Human characteristics	Specify user requirements	• **The users and their characteristics :** novice medical trainees who have not had much TTE examination experience • **The goals and tasks of the users:** self-paced learning with two proposed educational media– augmented reality (AR) application and computer screen-based multimedia instruction
Computer system and interface architecture Development Process	Produce design solution to meet user requirements	• Learners can experience with state-of-the-art learning materials which are relate to the interactive 3D computer animated graphics • 3D visual presentations of learning media can assist learners' conceptual understanding of spatial relationships between actual ultrasound images and cardiac anatomical structures • Development process of the proposed computer-based multimedia is detailed in section 3.5 • Development process of the proposed augmented reality (AR) application is detailed in section 3.6
	Evaluate the design against user requirement	• Clinical experts from the Queen Elizabeth Hospital Birmingham (QEHB) reviewed the learning content for the accuracy of clinical terminology and achieved a final consensus with the learning media prototypes. • Clinical experts from the Faculty of Medicine Siriraj Hospital, Mahidol University, Thailand, provided the initial feedback related to the usability and functionality of the proposed learning media.
	Design solution meets user requirements	• Implementing the achieved learning media into the intervention

3.4 The development of 3D cardiac models represented basic TTE windows

3.4.1 Rationale

3D visualisation has become increasingly important in graphic communications in medical science as there is a growing body of literature supporting the use of 3D interactive resources in medical education to make a great impact on the enhancement on novice learners' knowledge (Mitrousias et al., 2018; Zinchenko et al., 2020; Schwartzman and Ramamurti, 2021). Focusing on echocardiography education, novice medical students generally experience difficulties in learning the principles of echocardiography due to constraints in visualising cardiac anatomy from 2D into 3D images. In addition, mastering a complex knowledge base of basic TTE is quite a challenge for novice learners since it is based on theoretical knowledge and tacit knowledge—gained through clinical experience—for developing better conceptual understanding of spatial relationships between cardiac anatomical structures, ultrasound probe handling, patient position, and correct recognition of the imaging plane and orientation (Kydd et al., 2014; Dieden, Carlson and Gudmundsson, 2019). However, the most recent studies in literature related to echocardiography training focus on the utilisation of educational media rather than specifying techniques or procedural approaches to generate 3D visualisation (as presented in Chapter 2). Therefore, there is a lack of information on how 3D visualisation can improve the realism and efficiency of educational media and its impact on students' learning.

While the primary intent of this thesis pivots on the investigation of the different benefits of two educational technologies in facilitating self-directed learning experience about basic TTE, the starting step of the system development was to establish 3D digital assets used in the media—AR application and computer-based multimedia. In general, making 3D medical computer graphics is a collaborative work of 3D modelling artists who have an expertise to use appropriate computer skills to create realistic anatomical models under the supervision of subject matter experts or medical practitioners. This method was also applied to this thesis. The author decided to develop all new 3D modelling and animation for specific use for this research following the directions given in the textbooks and internet resources, and the guidance provided by cardiology specialists. Although the production of 3D digital assets from scratch was an incredibly time-consuming process, these final graphics were more usable and better suited to the requirements of this research than using commercially available 3D models found on any website marketplace, e.g., Sketchfab (Sketchfab,2021) or TurboSquid (TurboSquid, 2021), or CGTrader (CGTrader, 2021). Overall, the next subsection will detail the idea, specific software, and techniques used for the production process of 3D assets.

3.4.2 Overview of basic transthoracic echocardiography windows

In contrast to typical comprehensive TTE examination in which multiple views and scanning manoeuvre techniques provide a comprehensive structural and functional cardiac assessment, the basic or goal-directed approach to a TTE exam is way more focused on the rapid assessment of patients in critical care units or emergency settings. To prepare for situations mandating fast and precise diagnosis strategies, medical professionals must master the ability to obtain the best quality of echo images and quickly evaluate the life-threatening abnormalities in a critically ill or unstable patient. To date, many guidelines appear to share similar approaches of basic TTE used at the bedside in a time-sensitive manner, for example, Focused Assessed Transthoracic Echocardiography (FATE), Focused Echocardiography in Emergency Life Support (FEEL), Focused Assessment with Sonography for Trauma (FAST), Focused Intensive Care Echocardiography (FICE), and Critical Care Echocardiography (CCE) (Neskovic et al., 2012). Although the goal-directed echocardiography has a narrow scope and seems less complicated than a conventional comprehensive TTE, it is realised as the important initial assessment method for treating patients appropriately with greater speed and accuracy in the most challenging situations (Walley et al., 2014).

A major advantage of TTE is that it is non-invasive and risk-free procedure for patients. Moreover, the TTE machine can be set up in a short period of time, and it can be quickly deployed at the point of care, and readily repeated as required. According to a consensus within echocardiography recommended guidelines, basic TTE is deployed for diagnosing or confirming serious dysfunctions occurring in the heart or blood vessels, such as enlarged left ventricle (LV) or right ventricle (RV), tamponade (blood or fluid builds up in the space between the heart muscle and the outer covering sac of the heart), ventricular systolic function, and mitral valve regurgitation (the mitral valve does not close tightly). In general, the scope of basic TTE encompasses four main echocardiographic views which are explained as follows.

Parasternal long axis (PLAX)

The aim is to orientate the beam with the long axis of the left ventricle. The transducer is placed to left of the sternum in the 3rd, 4th, or 5th intercostal space with the maker pointed towards the right shoulder (11 o'clock). The qualified echo scan has to show the mitral valve and aortic valve in the centre of the image and the apex of the left ventricle is not seen.

List of the structures must be shown in the PLAX

1. Left atrium (LA)
2. Left ventricle (LV)
3. Mitral valve (MV)
- Anterior mitral valve leaflet (AMVL)
- Posterior mitral valve leaflet (PMVL)
4. Inter-ventricular septum (IVS)
5. Aortic valve (AV)
- Right coronary cusp (RCC)
- Non-coronary cusp (NCC)
6. Right ventricular outflow tract (RVOT)

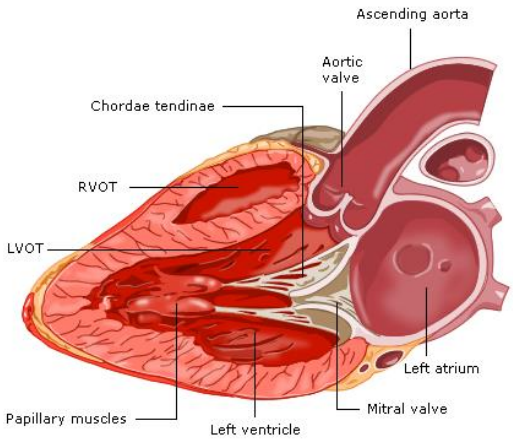


Figure 3.5: PLAX anatomy view (eIntegrity, 2020)

Parasternal short axis (PSAX)

The transducer remains in the intercostal space used to obtain the parasternal long axis view and is rotated clockwise 90 degrees so that it is perpendicular to the long axis of the left ventricle. The marker is orientated towards the left shoulder (2 o'clock). It is then tilted to sweep through from base to apex of the heart, obtaining several different views. The qualified echo scan has to show the left ventricle (LV) in the centre of the image. LV appearance shows round shape whereas the right ventricle (RV) shows in crescent shape.

List of the structures must be shown in the PSAX

1. Left ventricle (LV)
- Anterior (A)
- Anterolateral (AL)
- Inferolateral (IL)
- Inferior (I)
- Inferoseptal (IS)
- Anteroseptal (AS)
2. Right ventricle (RV)
3. Anterolateral papillary muscle (AL)
4. Posteromedial papillary muscle (PM)
5. Inter-ventricular septum (IVS)

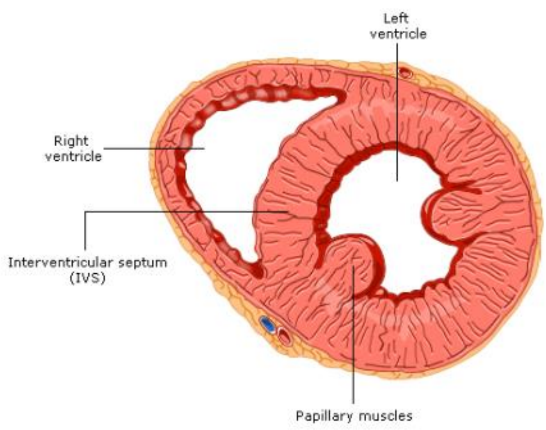


Figure 3.6: PSAX anatomy view (eIntegrity, 2020)

Apical 4 chamber (A4C)

The transducer is placed in the 4th or 5th intercostal space at the midclavicular line. The beam is directed up towards the patient's head, and the transducer is rotated so the marker points towards the left shoulder at around 3 o'clock. All four cardiac chambers (right atrium: RA, right ventricle: RV, left atrium: LA, and left ventricle: LV) must be shown in the image. The qualified echo scan has to show the interventricular septum (IVS) vertically and in the centre of the image.

List of the structures must be shown in the A4C

1. Left atrium (LA)
2. Left ventricle (LV)
3. Mitral valve (MV)
- Anterior mitral valve leaflet (AMVL)
- Posterior mitral valve leaflet (PMVL)
4. Right atrium (RA)
5. Right ventricle (RV)
6. Tricuspid valve (TV)
- Anterior tricuspid valve leaflet (ATVL)
- Septal tricuspid valve leaflet (STVL)
7. Interventricular septum (IVS)
8. Interatrial septum (IAS)
9. Lower left pulmonary vein (LLPV)
10. Right upper pulmonary vein (RUPV)

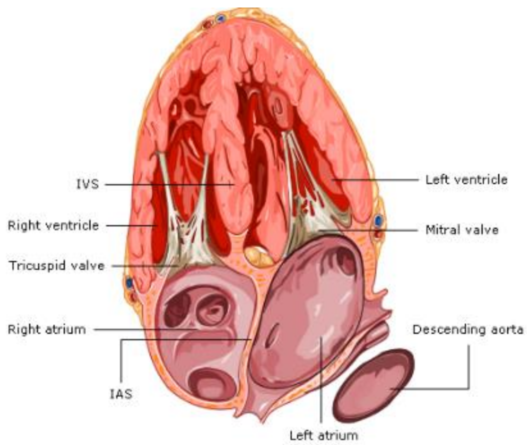


Figure 3.7: A4C anatomy view (eIntegrity, 2020)

Subcostal 4 chamber (S4C)

The transducer is placed to left of the sternum in the subxiphoid region of the abdomen with the index maker pointed towards the left (3 o'clock). The qualified echo scan has to show all four cardiac chambers and the interventricular septum (IVS) is shown obliquely to the image.

List of the structures must be shown in the S4C

1. Left atrium (LA)
2. Left ventricle (LV)

3. Mitral valve (MV)

- Anterior mitral valve leaflet (AMVL)

- Posterior mitral valve leaflet (PMVL)

4. Right atrium (RA)

5. Right ventricle (RV)

6. Liver

7. Tricuspid valve (TV)

- Anterior tricuspid valve leaflet (ATVL)

- Septal tricuspid valve leaflet (STVL)

8. Interventricular septum (IVS)

9. Interatrial septum (IAS)

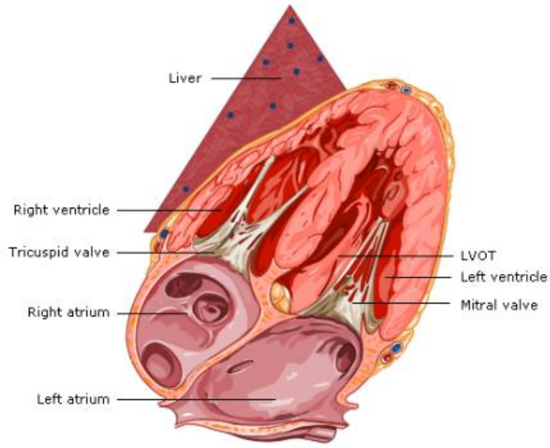


Figure 3.8: S4C anatomy view

(eIntegrity, 2020)

3.4.3 Development of 3D animated heart model for TTE education

Creation of the 3D whole heart model

The process started with a volumetric CT-based segmentation process for creating the first prototype of the whole heart 3D model in 3D Slicer. 3D Slicer is a free open-source software popularly used for image analysis and visualisation in medical and biomedical application. Several formats of the Digital Imaging and Communications in Medicine (DICOM) data set are compatible with Slicer, such as magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET). In this thesis, a cardiac CT scan, downloaded from an open-access medical image repository (Slicer.org, 2021) was used for image segmentation. 3D volume segmentation is the computerised algorithm method used for isolating interesting areas in imaging in terms of pixels or voxels (Moore, 2021). The selected CT scan was generated as a three-dimensional image showing greater details of heart structures including four chambers, five major vessels and coronary vessels.

The output volumetric image was exported as an STL, an acronym for stereolithography, file and imported into Autodesk 3ds Max (Autodesk, Inc., 2020). Techniques of retopology (the process of converting a complex or rough surface 3D model into a low resolution, simplified mesh of polygons) and texturing which is the process of applying 3D textures created from Adobe Photoshop (Adobe, Inc., 2020) to a 3D object were applied to create the realistic heart model as shown in Figure 3.9 and Figure 3.10.

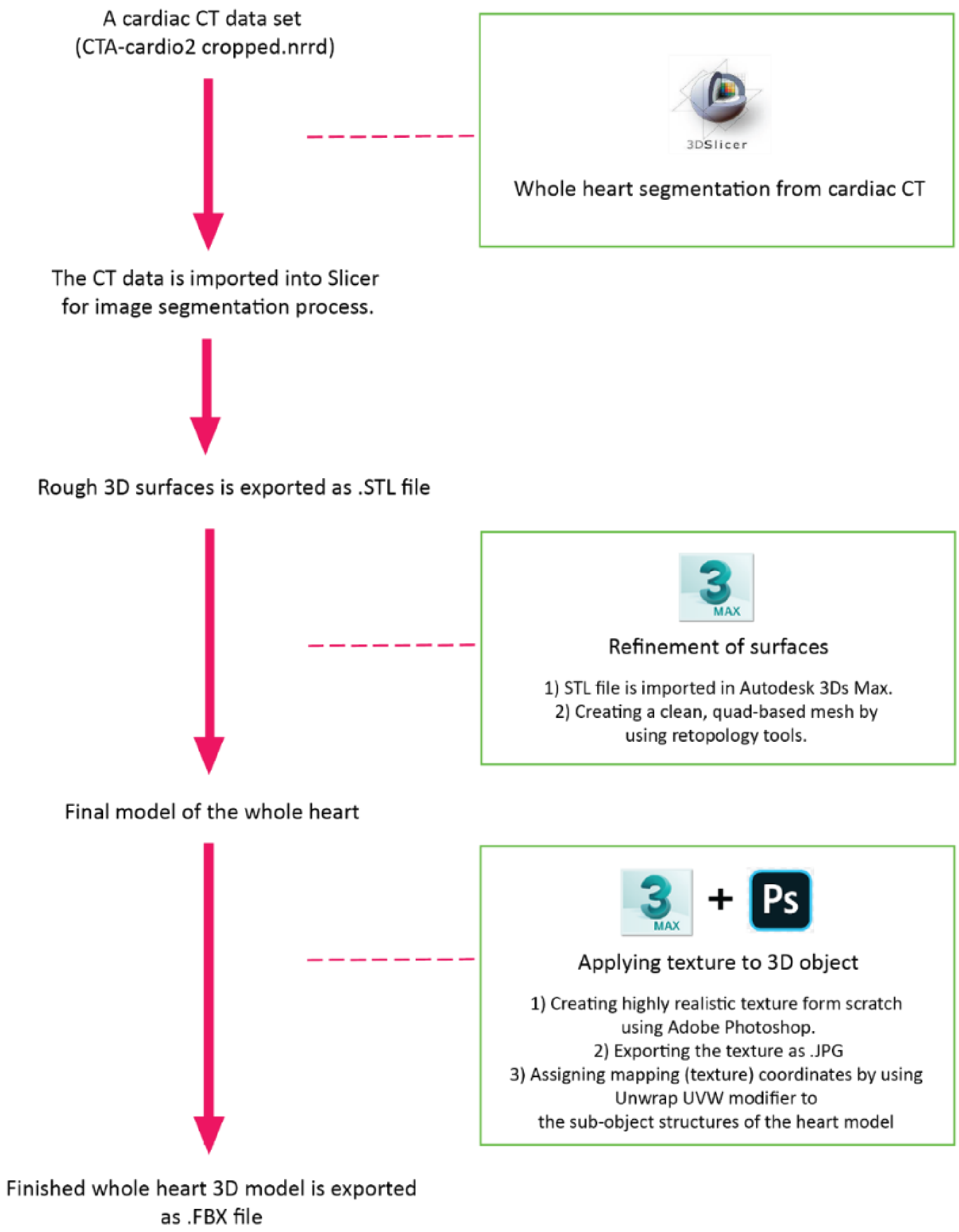
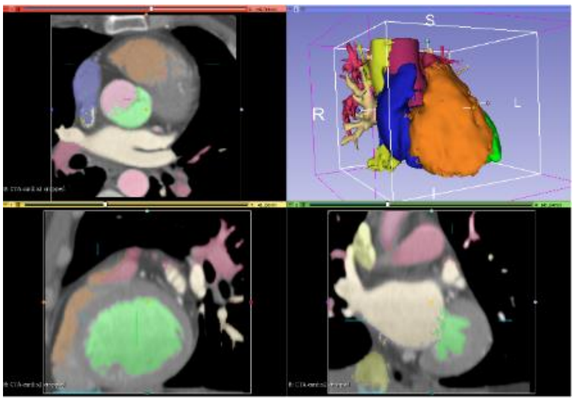
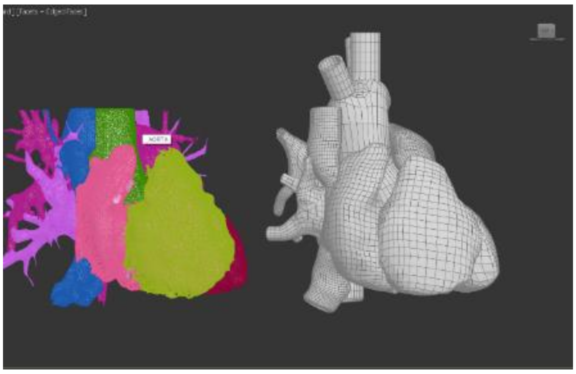


Figure 3.9: Workflow overview of software and data types used for developing the 3D whole heart model

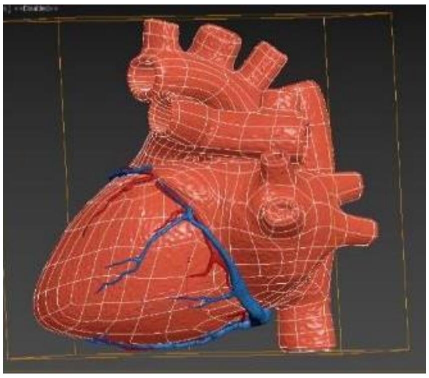
a)



b)



c)



d)

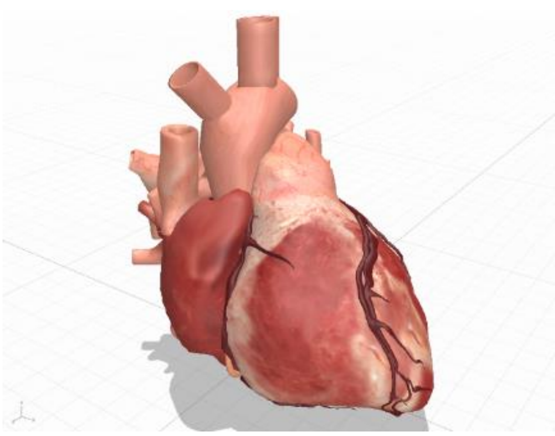


Figure 3.10: Screenshots of the development process of the whole heart model

a) Cardiac CT-based segmentation developed in 3D Slicer

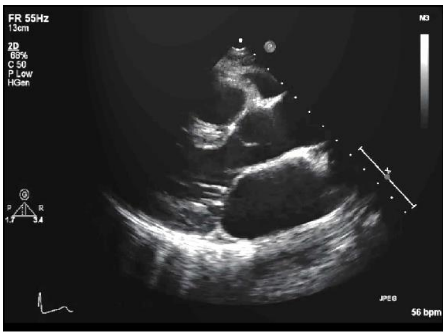
b) 3D retopology technique processed in 3ds Max

c) 3D model with a bump map which makes it appear to have an embossed and organic surface

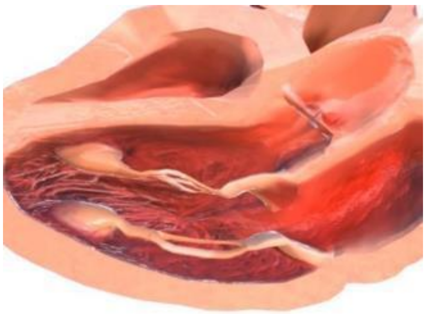
d) Finished whole heart 3D model with realistic texture

Creation of 3D models representing cardiac anatomical structures regarding basic TTE windows

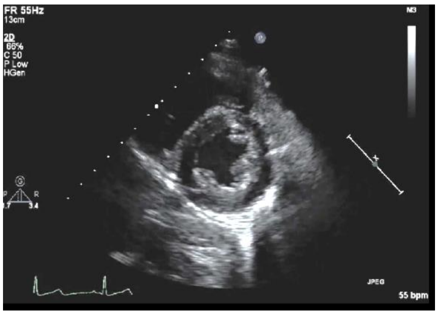
In the development of 3D models visualising each of the echo views—PLAX, PSAX, A4C and S4C views, there was a challenge which occurred during the content preparation step to find a real echocardiographic dataset for use in supporting the manual 3D modelling of required objects. Advice from the subject matter experts suggested that the use of retrospective anonymised patient data from the online storage would be the best solution. Using externally sourced data—which can be freely downloaded—has an advantage in timesaving and does not require formal ethical approval for usage. Unlike the development of whole heart model which started with the CT-based segmentation technique, the 3D digital models representing PLAX, PSAX, A4C and S4C were modelled within Autodesk 3ds Max and Adobe Photoshop using the anonymised adult echocardiography images and video loops obtained from the open source of freely available echo files (Echopedia.org, 2020) and the Aclands' video atlas of human anatomy (Wolters Kluwer Health, Inc., 2019) as references. 3ds Max was used in modelling, lighting, texturing, and animating 3D models. Photoshop was used for creating new textures specified on each of the 3D objects.



1a)

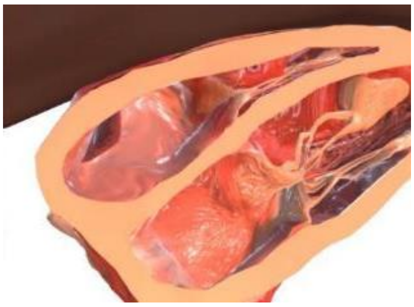


1b)



2a) 2b)

3a) 3b)



4a) 4b)

Figure 3.11: Creation of 3D cardiac models based on the video loops of actual echo images **(**anonymised patient data from free-online resources**)**

First row**:** the echo image of PLAX **(**1a**)**, the detailed structures of the PLAX 3D model **(**1b**)**; Second row**:** the echo image of PSAX **(**2a**)**, the detailed structures of the PSAX 3D model **(**2b**);** Third row**:** the echo image of A4C **(**3a**)**, the detailed structures of the A4C 3D model **(**3b**);** Fourth row**:** the echo image of S4C **(**4a**)**, the detailed structures of the S4C 3D model **(**4b**).** *Text not intended to be read*

Animating 3D heart models in 3ds Max

The animations of each 3D model were created to synchronise with the particular TTE views of the actual echo scan. Basically, the heart, blood vessels and blood are aggregated as the cardiovascular system. The two small upper heart chambers are called as the atria, whereas the two bigger lower chambers are the ventricles. The 3D animated representation aimed to demonstrate a cardiac cycle. A cardiac cycle or a heartbeat implies a complete series of events in which the atria contract (atrial systole) as the ventricles relax (ventricular diastole). Similarly, the ventricles contract (ventricular systole) as the atria relax (atrial diastole). Then both atria and ventricles relax for a short period. When the mechanism (contraction and relaxation) of cardiac muscle in the wall of the heart chambers happens, the cardiac cycle also generates pressure changes which cause heart valves to open and close (Nursing Times, 2018).

With 3ds Max, position, rotation, and scale of 3D heart models were animated in order to represent the continuous motions that simulated the anatomy and physiology of normal heart function. An animatable parameter of each 3D object was refined by using Auto Key Animation mode on or Set Key Animation mode in the keyframing mode at the bottom of the 3ds Max workspace. After finishing the animating process in 3ds Max, four 3D animated objects representing PLAX, PSAX, A4C and S4C were exported in FBX (*Film**box***) file which is an optimal exchange format that facilitates high-fidelity data exchange between two software packages —3ds Max and Unity (Unity Software Inc., 2020)

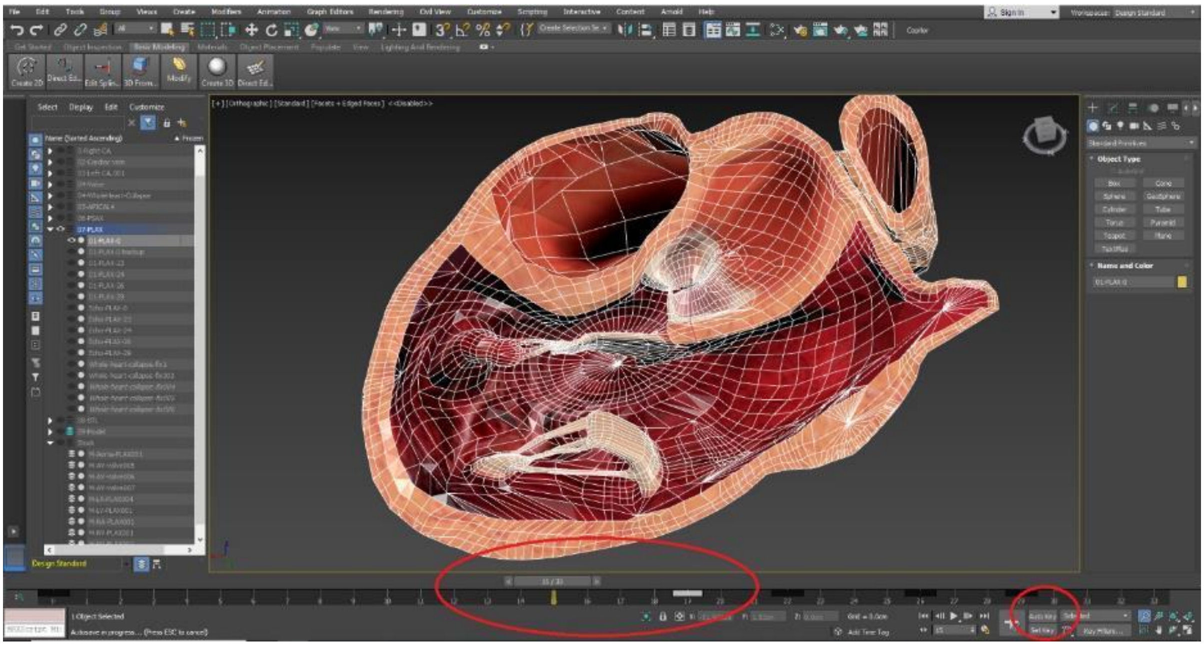


Figure 3.12: A screenshot of animation process of PLAX model**.** Red circles show the time slider, Auto Key and Set Key button which are used for controlling the transformation of the object**.** *Text not intended to be read.*

Other 3D models

As this thesis is driven by the aim of making the 3D visualisation scenarios represented in augmented reality (AR) application and computer-based multimedia for basic TTE education, other 3D objects including a ribcage, a human in supine position, and a transducer probe were required to complete the scene showing the spatial-relations between the heart structures, echocardiographic windows, and human surface anatomy. With the help of the team members of the Human Interface Technologies Team, University of Birmingham, who provided some 3D assets which they used from a project they worked on before, the author did not need to make a ribcage and a human in supine position from scratch. Meanwhile, a model of a transducer probe was generated by the author using simple poly-modelling technique in 3ds Max.

3.5 The production process of computer-based multimedia

As previously mentioned, this thesis aims to investigate the effectiveness of 3D visual presentation in learning media on medical trainees' conceptual knowledge improvement of basic TTE. The same design concept and 3D materials were rendered in two media formats with differing degree of visual fidelity: computer-based multimedia (lower visual fidelity) versus AR application (higher visual fidelity) which is equipped with a torso mannequin for enhancing learners' perception of TTE examination. This section outlines the concept and the production process of a computer-based multimedia system enhanced with 3D animated visualisation.

3.5.1 Creating interactive computer-based multimedia in Unity 2019.4

After the creation of individual 3D digital cardiac models regarding each of TTE windows—PLAX, PSAX, A4C and S4C, the subsequent refinement of the mesh for each anatomical structure was correctly determined and the animation was achieved through a multi-step process. All 3D animated models were imported in the Unity game engine (Unity Software, Inc., 2020) for the next step to develop the computer-based multimedia and AR application systems. These two learning systems were designed to have similar content regarding the concept of basic TTE but provide learners with a different a self-paced-learning experience.

The basic principle behind the computer-based multimedia's user interface (UI) design was to help learners easily navigate through a self-guided tutorial with offline option. The Unity 2019.4 software was used for the development of multimedia in a format compatible with PC, Mac & Linux Standalone. Focusing on the user interface (UI) of the multimedia module where an interactive communication between learners and educational content occurs, four types of the Unity scene of user interfaces were developed for this research project including the homepage, the introduction, 'the anatomy'—details of anatomical structures of the heart based on the different basic echocardiographic views, and 'the image optimisation'—the method of the use of transducer to obtain and improve the visual quality of an echocardiographic image. The two first scenes were used as the main 'welcome' pages which provide a brief introduction of TTE education to a learner. The third scene, 'the anatomy', was made up for synchronising two different presentations of basic TTE views: an actual video clip of echo scan and a 3D short animation. The UI scene was designed to enable learners literally to construct their understanding of structures visualised with echocardiogram in a more integrative way. The final scene design was 'the image optimisation' aimed at helping the learner to recognise the spatial relationship between surface anatomy of the thorax (principally focusing on the ribcage) and methods in performing echocardiography tasks to obtain each view. Collectively, the multimedia tutorial that draws on active learning, engaging and easily manipulable graphical structures to learn cardiac anatomy represents a move beyond using a textbook alone or instructor-led training.

By focusing more on the interactive features in the UI, there is another terminology that should be mentioned, graphical user interface (GUI). GUI refers to a system of interactive visual objects where the user can interact with a computer or electronic device (Levy, 2018). Visual indicator representations such as symbols, graphical icons, buttons, menu bar and text-based dialog boxes are generally considered under the umbrella of GUI. In this thesis, interactive features including an interactive menu, control of viewpoint, and the ability to control the visibility of structures were incorporated in GUI which encourages active learning through using the multimedia interface (Figure 3.12).

Adobe Photoshop (Adobe, Inc., 2020) and Adobe Illustrator (Adobe, Inc., 2020) were used to develop background and sprites (a general term encompassing simple 2D graphical objects, buttons, and icons) for the multimedia's user interface. The GUI included in the scenes of the multimedia system were implemented as buttons including *Labels On, Labels Off, Pause, Home, Back, Next,* and *Exit* which were provided for enabling the learner to navigate easily through the tutorial.

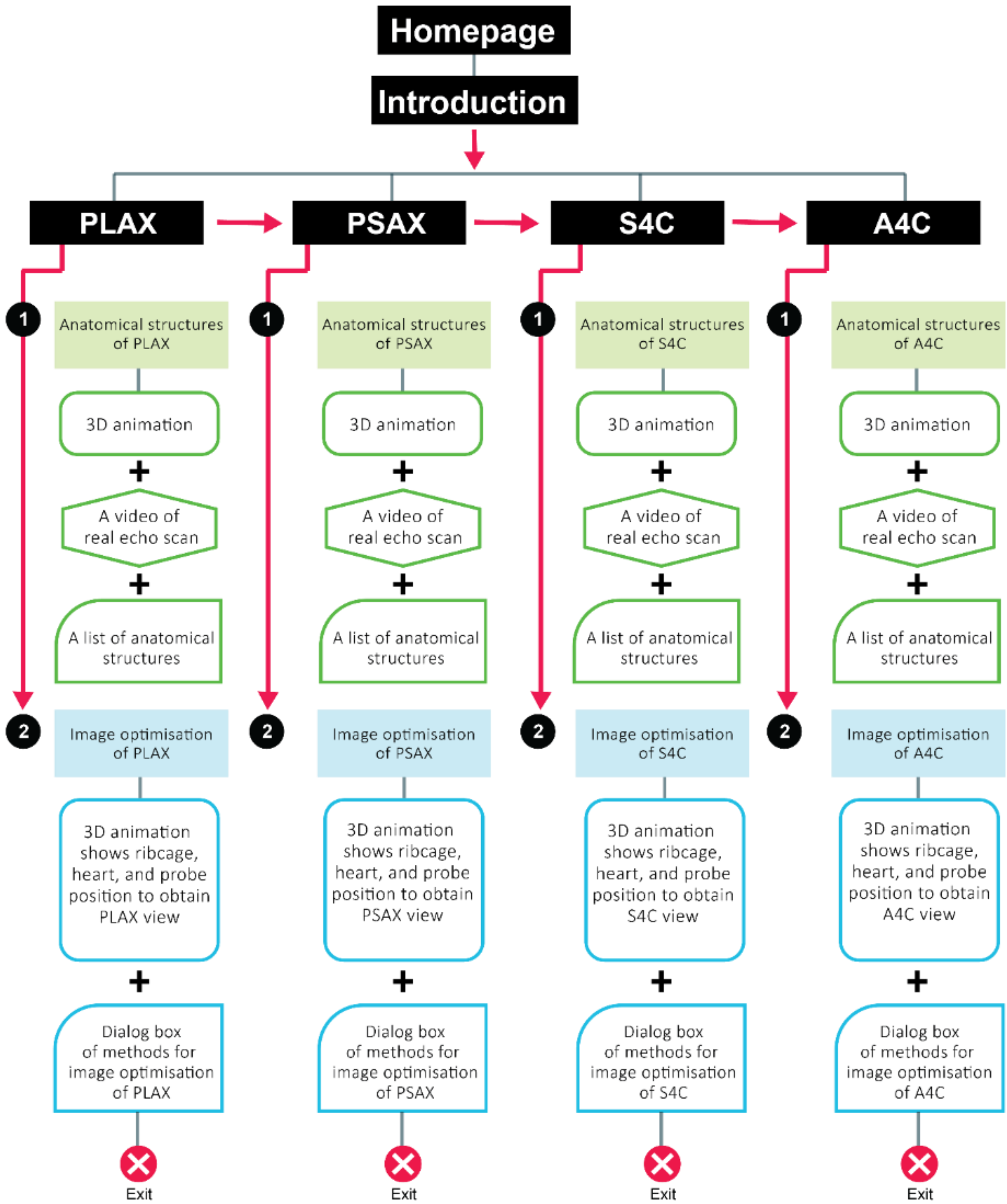


Figure 3.13: Content of multimedia system organised in flowchart.

User Interface within a homepage

The learner was first greeted with a homepage and he/she was able to press 'Get Started!' button to move forward to the 'introduction' page.

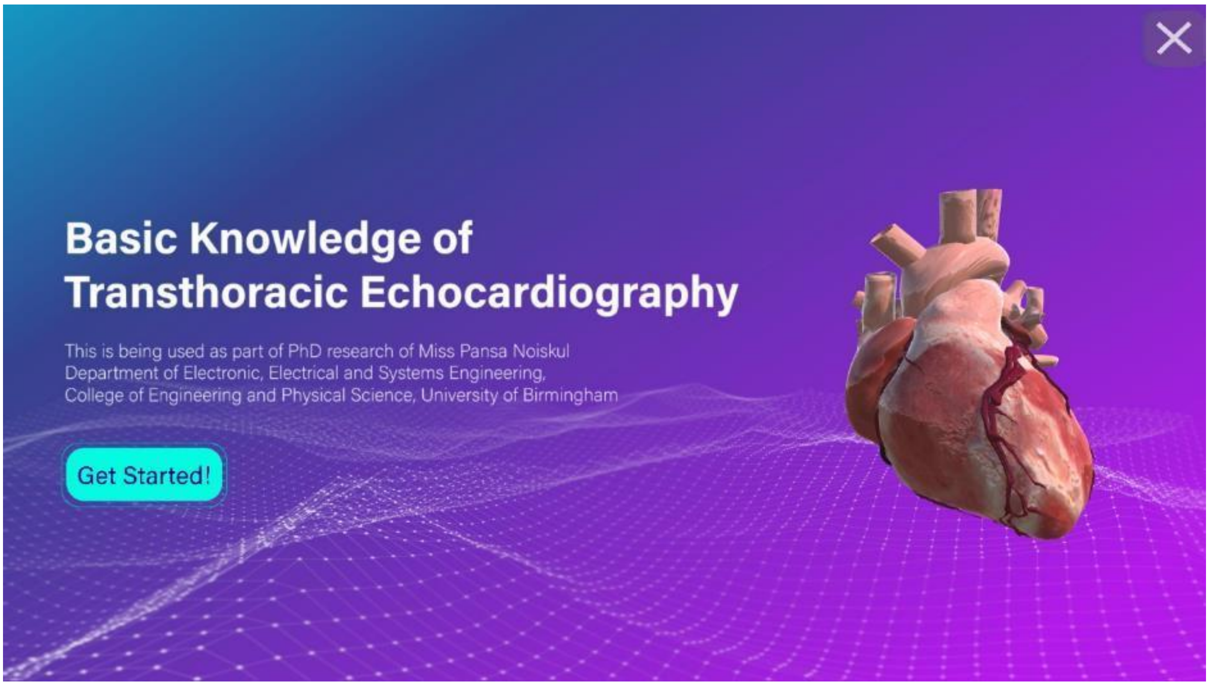


Figure 3.14: A homepage of the multimedia module **'**Basic Knowledge of Transthoracic Echocardiography**'**. *Text not intended to be read.*

User Interface within an introduction page

This page provided a brief introduction about basic TTE. The left side menu bar would activate in the green colour referring to the recent content, whereas the right below bar consisted of three icon buttons that allow users to take actions with a single tap.

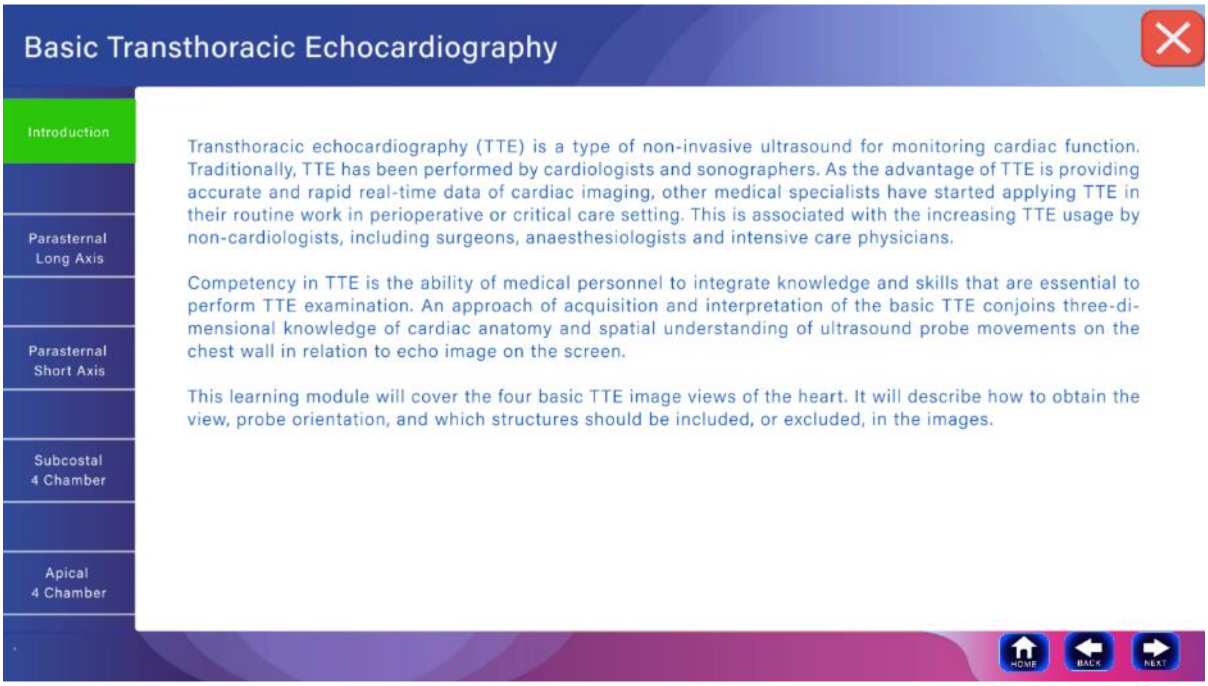


Figure 3.15: An introduction page**.** *Text not intended to be read.*

User Interface within the learning module: the anatomy

The user interface appearing in this scene contained three parts including a video loop of 3D animation, a video loop of actual echo scan, and the dialog box narrating the structures found in different basic TTE windows. In general, the 3D animation and the video loop of echocardiogram have synchronised moves. A user could be able to press a button 'Labels On' for freezing the 3D animation and showing details and position of anatomical structures. The left side menu bar would activate in the green colour according to each echo views.

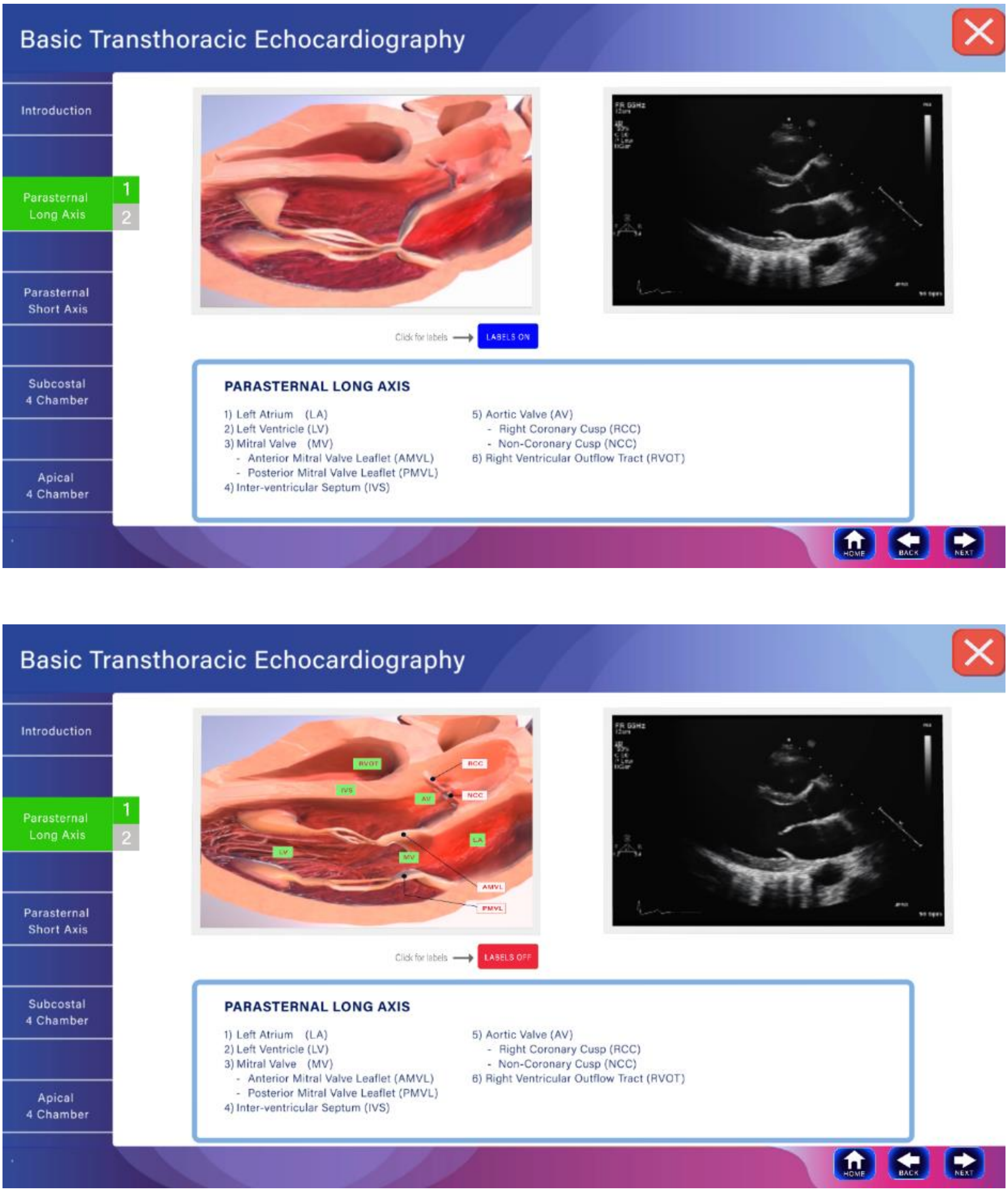
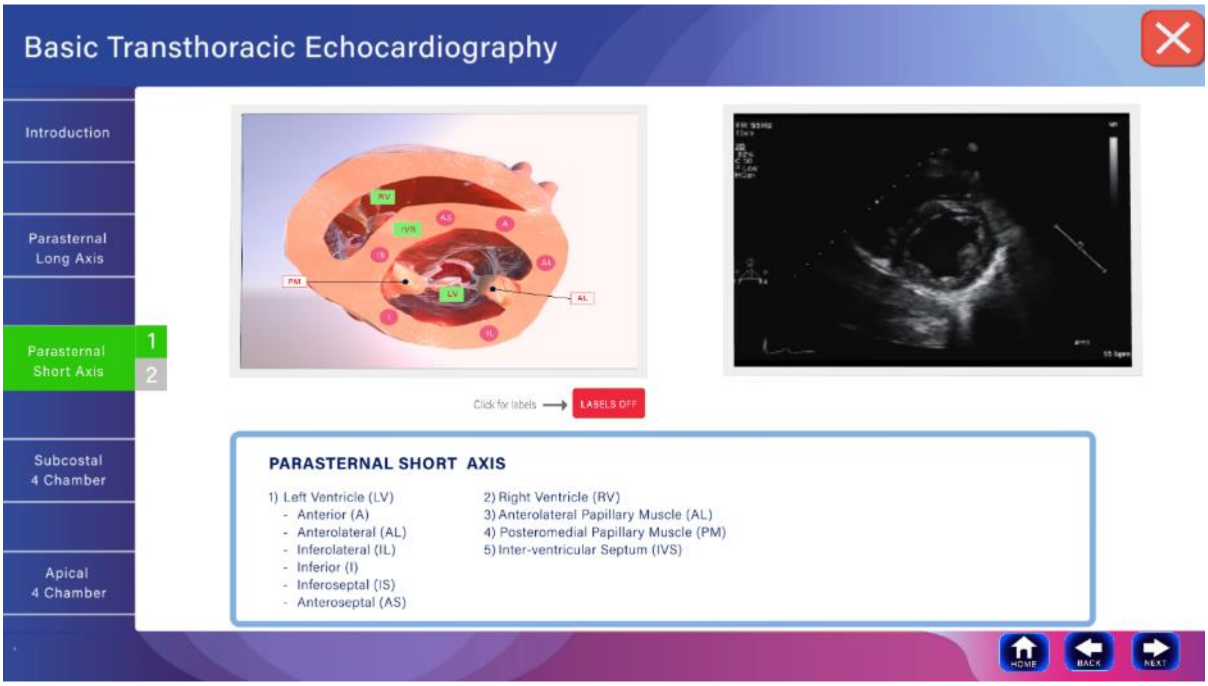
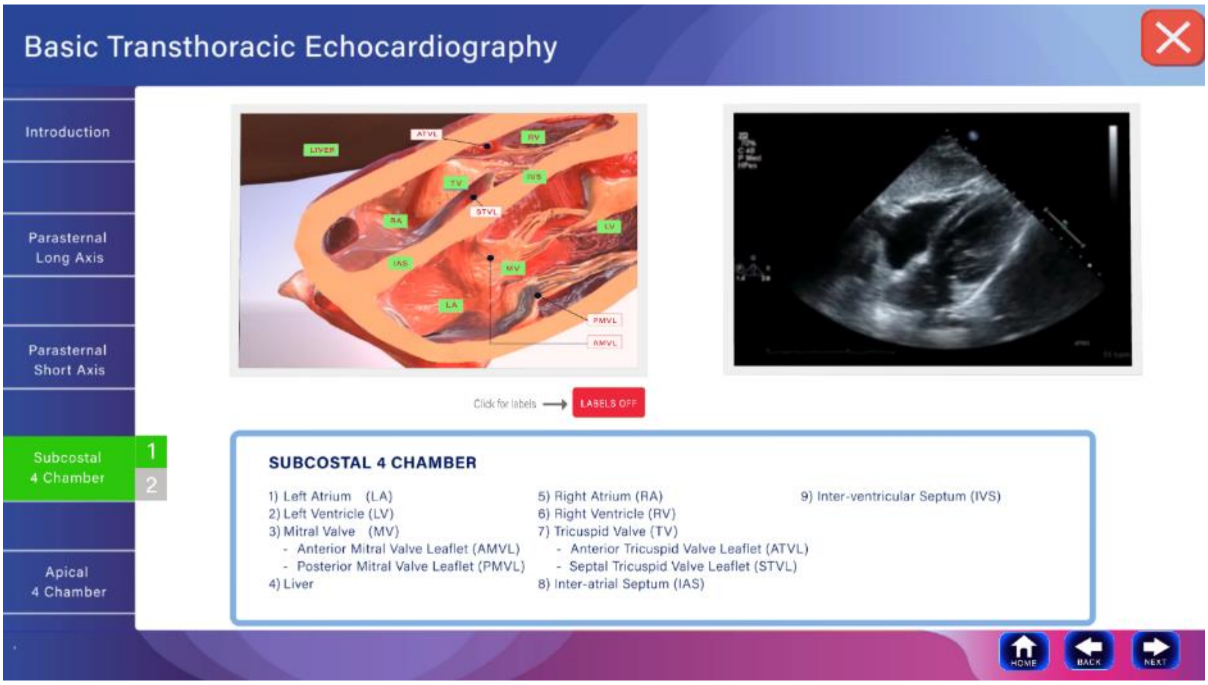


Figure 3.16: A user interface (UI) showing the anatomy scene of the PLAX view.

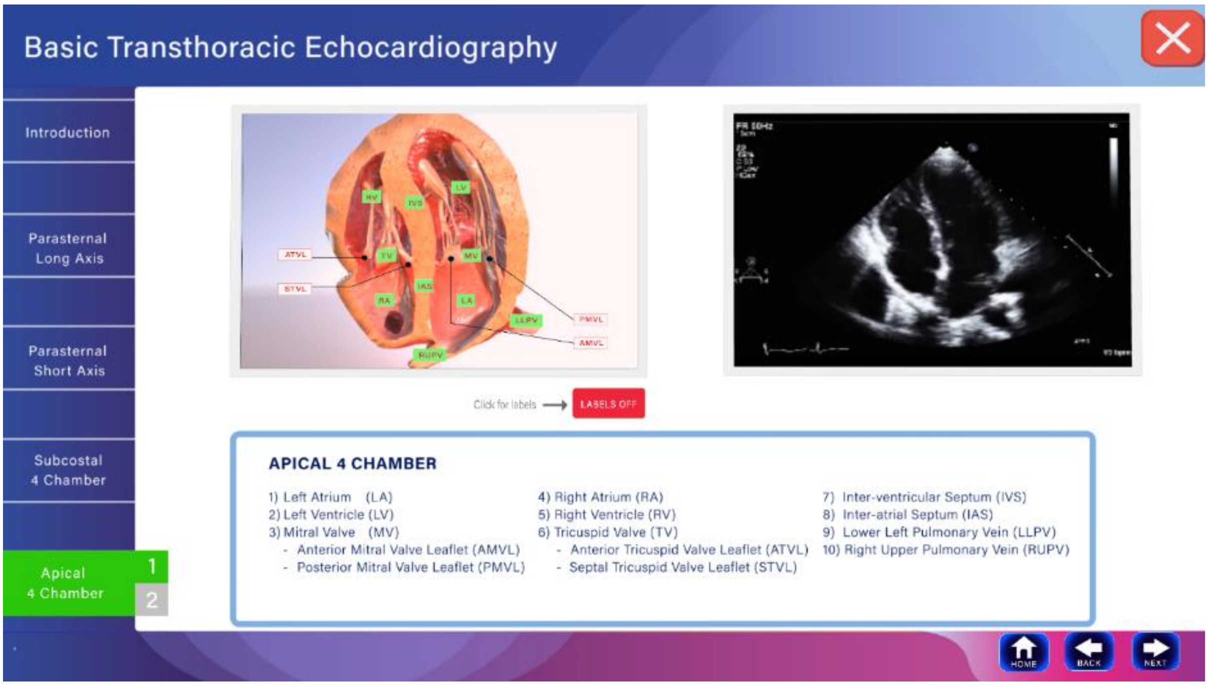
Top: the 3D animation (left) and video loop of actual scan (right) automatically have synchronised moves. Bottom: the 3D animation (left) was frozen after clicking the tab 'Labels On' and the labels pointed towards the structures. *Text not intended to be read.*


Basic Transthoracic Echocardiography
Introduction
Parasternal Long Axis
Parasternal Short Axis
1
2
Subcostal 4 Chamber
Apical 4 Chamber
RV
IVS
AS
A
IS
AL
PM
LV
AL
I
IL
Click for labels
LABELS OFF
PARASTERNAL SHORT AXIS
1) Left Ventricle (LV)
- Anterior (A)
- Anterolateral (AL)
- Inferolateral (IL)
- Inferior (I)
- Inferoseptal (IS)
- Anteroseptal (AS)
2) Right Ventricle (RV)
3) Anterolateral Papillary Muscle (AL)
4) Posteromedial Papillary Muscle (PM)
5) Inter-ventricular Septum (IVS)
HOME
BACK
NEXT

(a)


Basic Transthoracic Echocardiography
Introduction
Parasternal Long Axis
Parasternal Short Axis
Subcostal 4 Chamber
1
2
Apical 4 Chamber
LIVER
ATVL
RV
TV
IVS
STVL
RA
LV
IAS
MV
LA
PMVL
AMVL
Click for labels
LABELS OFF
SUBCOSTAL 4 CHAMBER
1) Left Atrium (LA)
2) Left Ventricle (LV)
3) Mitral Valve (MV)
- Anterior Mitral Valve Leaflet (AMVL)
- Posterior Mitral Valve Leaflet (PMVL)
4) Liver
5) Right Atrium (RA)
6) Right Ventricle (RV)
7) Tricuspid Valve (TV)
- Anterior Tricuspid Valve Leaflet (ATVL)
- Septal Tricuspid Valve Leaflet (STVL)
8) Inter-atrial Septum (IAS)
9) Inter-ventricular Septum (IVS)
HOME
BACK
NEXT

(b)

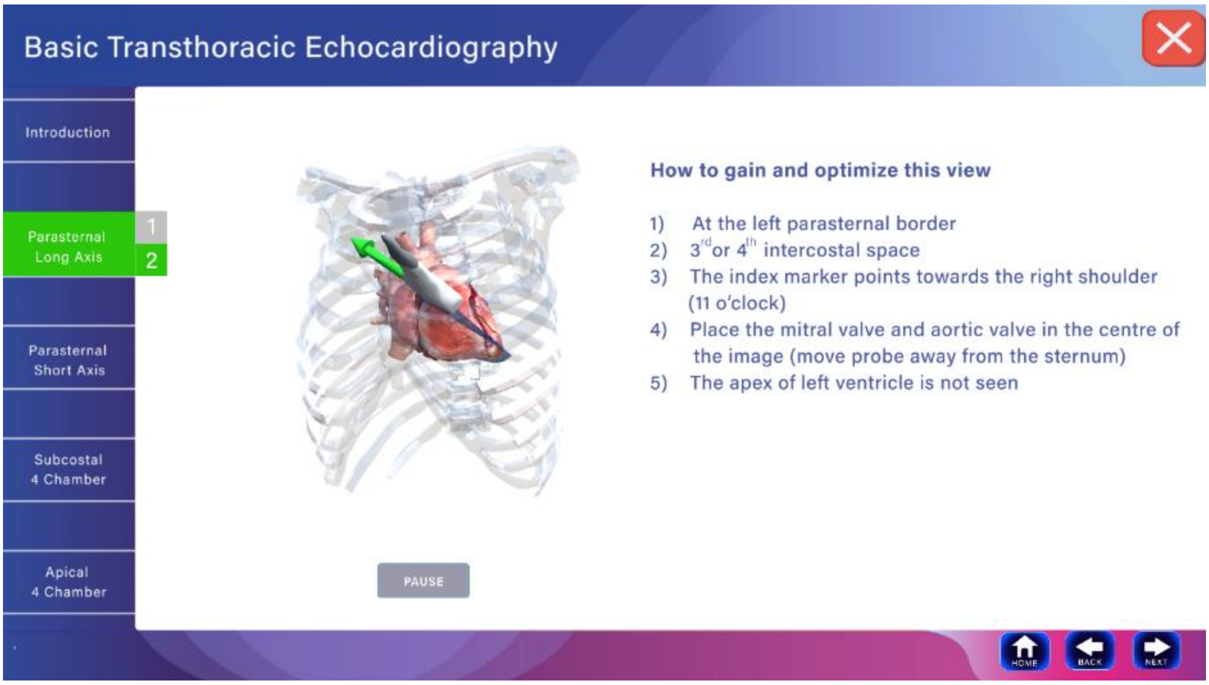


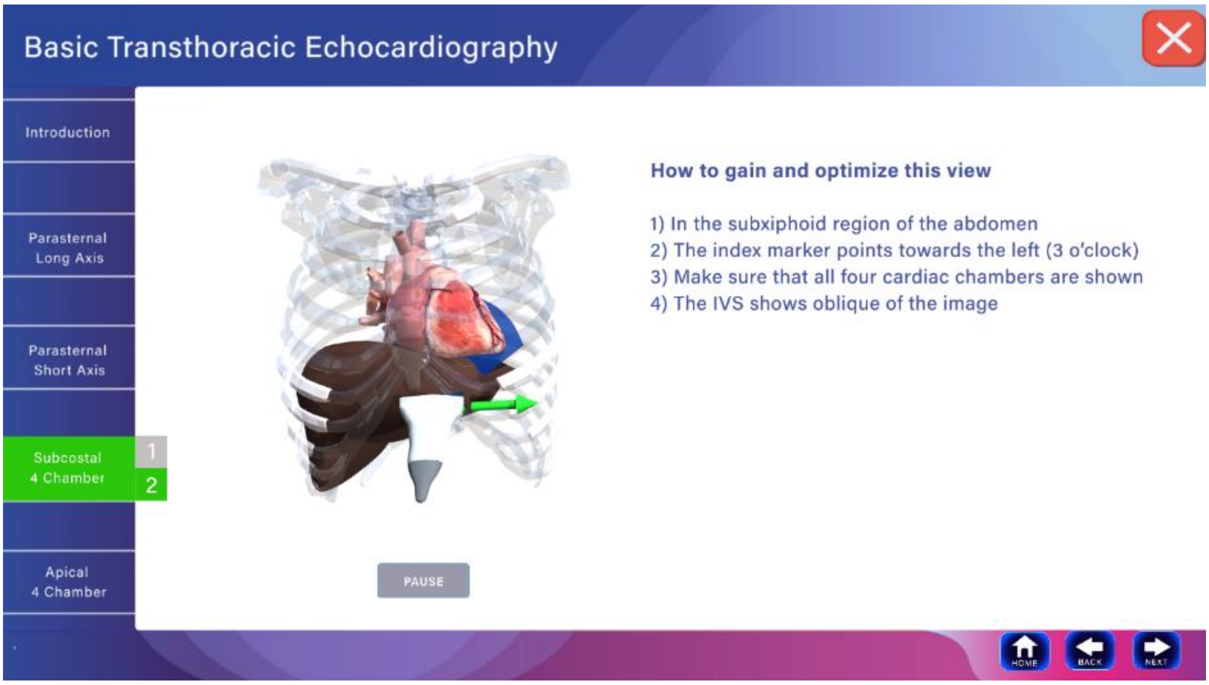
(c)

Figure 3.17: Screenshots of the 'anatomy' scene of the multimedia module. Top **(a):** Parasternal Short Axis view**.** Middle **(b):** Subcostal 4 Chamber view**.** Bottom **(c):** Apical 4 Chamber view**.** *Text not intended to be read.*

User Interface within the learning module: the image acquisition

The user interface showing in this scene is composed of two sections. The left side of the scene showed 3D animated ribcage, heart and a transducer probe having synchronised moves. The right side of the scene was a dialog box mentioning the method for obtaining the good quality of required echocardiogram. In general, the 3D animation portraying the spatial relationship between human anatomy and a transducer probe would show as the rotating movement. A user could press the button 'Pause' for stopping the movement and investigating the anatomical view as he/she would like to. The left side menu bar would activate in the green colour according to each echo views.





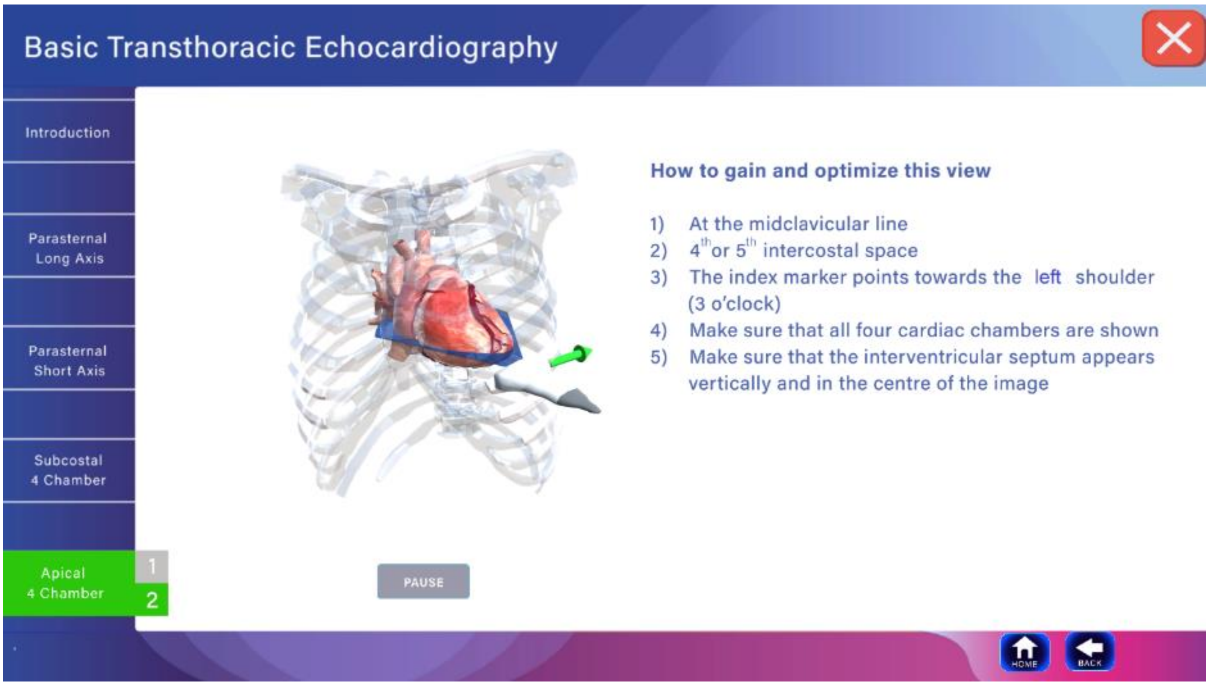
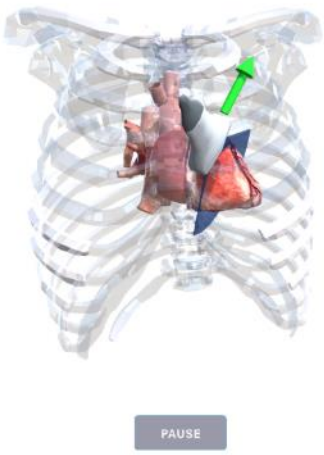
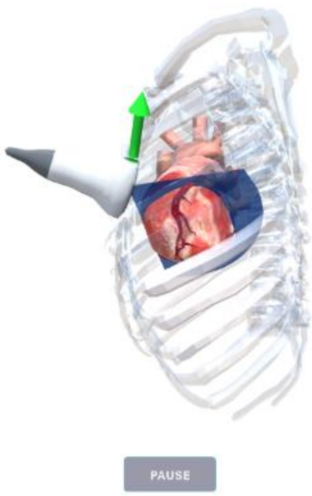


Figure 3.18: Screenshots of the **'**image optimisation**'** scene of the multimedia module. Top **(**a**):** Parasternal Long Axis view**.** Middle **(**b**):** Subcostal 4 Chamber view**.** Bottom **(**c**):** Apical 4 Chamber view**.** *Text not intended to be read.*

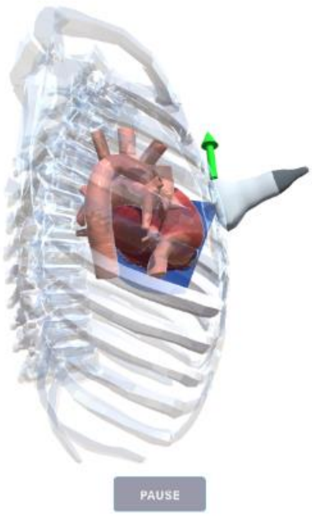


(a)



(b)

(c)



(d)

Figure 3.19: Closely cropped images of the **'**image optimisation**'** of the PSAX scene focussing on the 3D rotating animation show the interactive action when a user clicks on the button **'**Pause**'**, the animated model of PSAX view will cease at any position that he**/**she wants**. (**a**):** anterior view, **(**b**):** left lateral view, **(**c**):** posterior view, and **(**d**):** right lateral view

3.6 The production process of marker-based AR application

The main objective of the development of AR application was to augment an artificial 3D representation of an actual echocardiography exam. In contrast to learning through the computer-based multimedia module, an AR scene is mostly about spatial awareness. In general, spatial ability refers to the cognitive functions of a human to understand, remember, and imagine the spatial relations among objects and space in different viewpoints (Nagy-Kondor, 2017). As the demand for utilising AR application has grown, researchers have endeavoured to investigate innovative solutions for adapting AR platforms into the real practice. Goebert (2020) presented that most recent AR applications can be categorised into four types of delivery systems: wearable head-mounted display AR, projector-based AR, broadcast AR, and mobile device-based AR.

Using a wearable head-mounted display was not considered to be best option for this thesis as the prospective experiment was commenced during the COVID-19 pandemic where the perceived seriousness of a disease was an important deterrent of using wearable head-mounted display (HMD). In addition, Suman et al. (2020) concluded that the COVID-19 virus is thought to be able to survive up to 72 hours on plastic which is the main material in commercial VR or AR headset production. The process of quarantining an AR headset or frequently decontaminating it for setting the experimental protocol might be time-consuming and unable to provide sufficient guarantee of preventing transmission of COVID-19 during AR sessions. Conversely, mobile marker-based AR application refers to an integrated system (hardware and software) including a computing device, an output device (mobile or tablet), a camera, a tracking system, 2D image (s) used as predefined markers, and a physical object or space to stitch the real and the virtual simulated environment together (Jang, Ko, Lee and Kim, 2018). The great benefit of mobile marker-based AR is a simple interaction to use touch screen with the fingers. Therefore, mobile marker-based AR system was considered as the best alternative AR system being used for the thesis.

3.6.1 Developing the interactive marker-based AR application

As previously mentioned in the Chapter 2, AR is a type of digital experience in which a user's physical world is augmented (or supplemented) by virtual contents including 2D or 3D graphics, sound, and video. The core concept of the AR application in this present thesis is to use similar components (2D and 3D assets) as the multimedia module used earlier but greater emphasis on the app functionalities which stimulate learners' cognitive perception to comprehend spatial relationships among surface anatomy, cardiovascular anatomy, and methods of handling transducer position for visualising different views of basic TTE. To understand the concept of the development, the following subsections will explain the core components utilised in the whole process. The overall AR system consists of four major components: a torso mannequin, authoring software for AR application, a marker board, and an output device. Each individual part of the system is explained in more details below.

3.6.1.1 The development of a torso mannequin

A torso mannequin was fabricated by the author in December 2018 – January 2019. Before the COVID-19 pandemic, the torso mannequin was intended to be developed as part of a mixed reality (MR) simulator for basic TTE education. The original design in the first proposal of the MR simulator aimed at exploiting the torso mannequin for generating tangible user interactions in the MR experience. User's interactions, in the first proposal, were by a portable force sensor integrated in the torso mannequin. Interactions between force sensor and mannequin were designed to generate 3D graphic visualisation by the learners, via the wearable MR headset. In sum, the proposed MR simulator would assist medical trainees to practise psychomotor skills of basic TTE examination, whereas their palpable sense of actual TTE examination was constructed by touching the surface of the fake skin (silicone-based material) of the mannequin.

The COVID-19 pandemic affected the author to in carrying out this research. According to World Health Organization's recommendations (World Health Organization, 2023), there are many ways to prevent the COVID-19 transmission including physical (social) distancing and avoiding using communal items. For this research, using the proposed MR simulator could be identified as a risk factor that might be involved in the COVID-19 disease transmission because the simulator was meant for communal use for the group of the target participants of the study. The wearable AR headset in the MR system is placed against the risk areas of infection—the eyes, the nose and the mouth. Moreover, MR controllers come into close contact with the hands which are a key route of transmission for Coronavirus. Therefore, the plan of using MR simulator in this study was rejected and the mobile marker-based AR application was developed instead. In terms of the utilisation of the torso mannequin, it was still applied in the AR application as the tangible object augmented with superimposed 3D virtual models. The process of making the mannequin can be seen as follows.

Sketch and design

The author planned to fabricate a torso mannequin which can represent five standard views of echocardiography: parasternal long axis view (PLAX), parasternal short axis view (PSAX), apical 4 chamber view (A4C), and subcostal 4 chamber (S4C). These relate to anatomical structures of the heart and ribcage. More details of probe orientation are given in Table 3.5.

Table 3.5: Echo imaging windows and transducer orientations (Mitchell et al., 2019)

Windows	Transducer orientations
Parasternal Long Axis (PLAX)	Transducer 3-5 cm to the left of the left sternal border at the 3rd to 5th intercostal space The probe marker pointed towards the patient's right shoulder
Parasternal Short Axis (PSAX)	Transducer 3-5 cm to the left of the left sternal border at the 3rd to 5th intercostal space The probe marker pointed towards the patient's right shoulder Transducer rotated 90 degrees clockwise from the PLAX view
Apical 4 Chamber	Transducer placed at the point of maximum impulse (PMI) or the 6th intercostal space in mid-clavicular line The probe marker pointed to the patient's left
Subcostal 4 Chamber	Place the transducer down to the sub-xiphoid position The probe marker pointed to the patient's left shoulder (3 o'clock)

The purpose of using a mannequin is to represent physical structures of the patient for TTE training. In addition to anatomical landmarks as mentioned above, an artificial skin sheet is included in the production plan for enhancing users' sense of touch. According to the study of measuring the thickness of human skin which was conducted by Oltulu *et al.* (2018), skin thickness of the male chest ranges from 6.052 ± 2.435 mm.

Therefore, the author had designed the prospective mannequin that would be composed of two parts: a rubber-based skin sheet and a solid structure of male torso. The thickness of artificial skin sheet is no more than 1 cm. regarding the anatomy of male chest as mentioned. The simulated skin includes some visible muscles of the trunk such as Pectoralis major and Rectus abdominis. Solid materials used for the ribcage are important for supporting the user's sense of palpation for TTE training, for example, the suprasternal notch and xiphoid process of sternum. A final design draft is shown below.

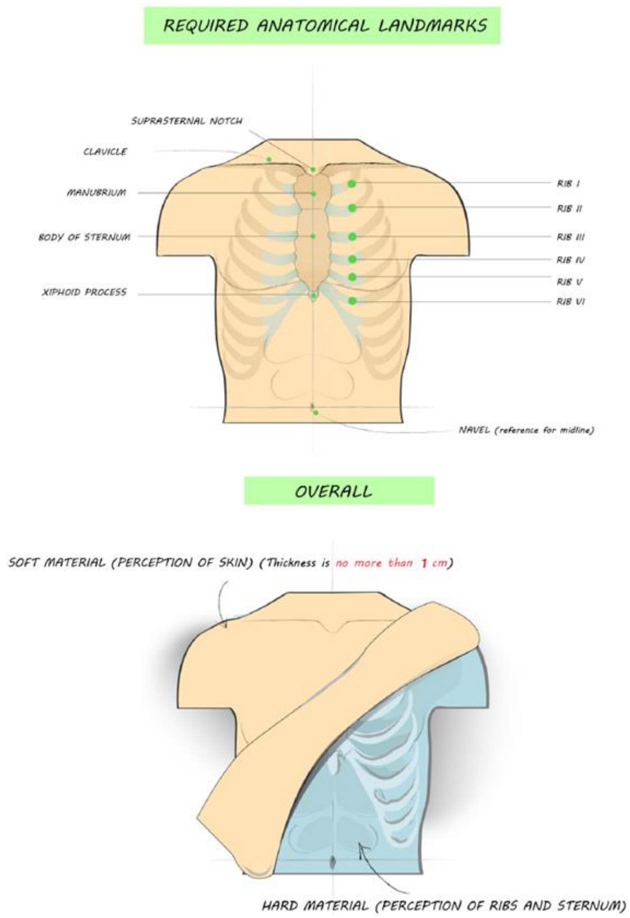


Figure 3.20: Mannequin Design Illustration

(Original illustration created by the author, Pansa Noiskul)

Mannequin production process

Making the prototype: Plasticine

The prototype was basically formed out of the non-toxic plasticine. The solid materials such as cardboard box, wooden stick and aluminium wire were formed as the armature. The armature is a solid structure that supports the plasticine in the required position. The suitable anatomical landmarks and positions were based on the sketches and the references (e.g., textbook, internet resources)

According to the initial plan, this plasticine would be moved to the medical model lab, Medical Education Technology Centre in Thailand for the next procedure. Unfortunately, the plasticine was too damaged to be further developed due to the transportation from the UK to Thailand. So, the prototype materials and methods were changed to achieve the final mannequin through the time limit.

Figure 3.21: The torso plasticine

Figure 3.22: The plastic-based manufactured mannequin

Due to the time limitation (within a month), technicians at the medical model lab at my sponsoring hospital in Thailand advised me of an alternative solution for making the prototype—constructing the required structures onto the existing manufactured mannequin. A commercially manufactured mannequin made from thermoplastic was purchased. As seen in the picture, there are some parts of anatomical structures, the rib cage, that needed to be completed.

Making the prototype: constructing required structures onto the existing manufactured mannequin— the rib cage

According to the design diagrams, anterior parts of the rib cage would be additionally built up. Epoxy putty resin was attached to the plastic-based mannequin in building up the rib cage structure; the applied epoxy putty (Figure A4) was then cultivated to create the required structures by using modelling tools.

Figure 3.23: Hand-mixable epoxy putty resin

Figure 3.24: Building up the rib cage by using the epoxy putty resin

Figure 3.25: A completed solid structure of the rib cage

Mouldable epoxy putty was sculpted into the rib cage shape as well as imitating the appearance of abdominal muscles— Rectus abdominis, which adhere to the plastic surface of the mannequin. This entire process lasted for 2 weeks to complete the essentially anatomical landmarks as planned and to strengthen the putty formation.

Making the prototype: Constructing required structures onto the existing manufactured mannequin— the skin sheet

The simulated skin sheet is applied to the mannequin for assisting the realistic touch and anatomical guideline for transthoracic echocardiography learning. A use of non-toxic plasticine was moulded into the figure of torso muscles, abdominal muscles and nipples to cover on top of the mannequin, as shown in Table 3.6.

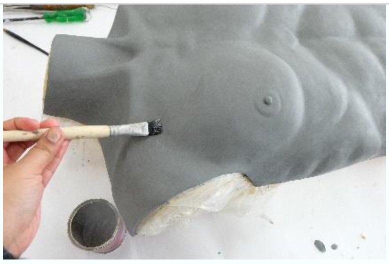
Table 3.6: Sculpturing the skin sheet of plasticine

Preparation		Apply a coating of a release agent (petroleum jelly) and cover up with a cling film to prevent the plasticine from adhering to the epoxy putty substance.
Sculpturing		
		

Figure 3.26: A completed plasticine represented as the form of muscles and skin

Making of two-part skin mould of the skin sheet

Table 3.7: Moulding process

Preparation		Clean up the plasticine surface by using turpentine before starting moulding process.
Moulding Procedure (1st part)		Build a clay wall and shores around the prototype so that these structures can hold the plaster without leaking.
		Apply a coating of a release agent (petroleum jelly) over the prototype in order that it will be easily removed from the mould.
		Mix a finely ground plaster with water in a container.
		Quickly place a first layer of the plaster over the prototype. Leave it to dry for 2 hours.

		
		Mix a fine plaster with water and acrylic colour
		Apply a coloured plaster over the prototype as the second layer. Leave it to dry for 2-3 hours.
		Mix a fine plaster with the asbestos fibre and place it as the third layer over the prototype in order to provide solidity to the mould and prevent it from breaking
		Leave the plaster for a day in order to completely get rid of dampness, then removed from the mannequin prototype. The plasticine is still adhered to the mould

Moulding Procedure (2nd part)		Adhere the tube-shaped clay and wood sticks to the plasticine. These will be channels for pouring silicone rubber into the plaster mould. ** The 1st plaster mould has to be brushed with a release agent (petroleum jelly) over its surface. Otherwise, the 2nd mould will be unable to detach*
		Prepare the plaster for moulding. Place the mixed plaster over the 1st mould. Leave it to dry for a day. Once the clay is removed from the mould.

Figure 3.27: A completed two-part skin mould of the skin sheet

Casting and Demoulding

Table 3.8: Casting procedure with the silicone rubber

Preparation		Apply soapy water to the mould surface for preventing it from adhering to silicone rubber
		Measure equal amounts of Room temperature vulcanising (RTV) silicone rubber Part A and Part B. Mix Part A, Part B and a small amount of skin-tone liquid silicone pigment together.
		Make sure to scrape the sides and bottom of mixing container several times.
		Place the container of mixed silicone rubber into a silicone vacuum machine. Wait for 7-10 minutes.

Table 3.9: Preparation of materials for casting process

Casting procedure		Move the silicone container out from the vacuum machine. Then pour the silicone rubber through the prepared channels of the mould
		Make sure that the silicone rubber is completely filled into the mould. The silicone must reach the highest point of the channels and then seal the channel hole with clay
		Leave the silicone rubber for a night in order to ensure it is completely set, and then slowly demould casting with the chisels and hammers.
		

Finishing the skin sheet

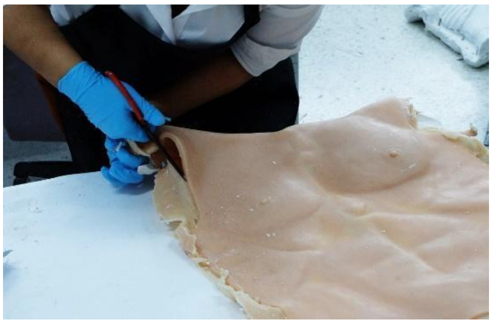
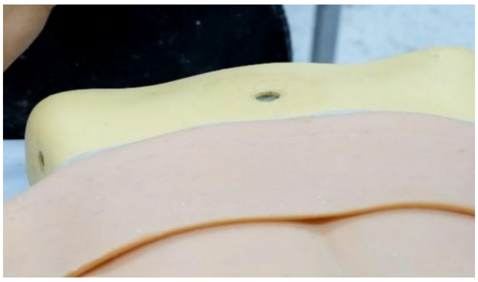


Figure 3.28 Clean the surface

Figure 3.29 Trim unwanted parts

Figure 3.30 Fill in small damaged areas or fissures caused by the plaster mould with skin-tone silicone sealant

Assembling the mannequin and the skin sheet



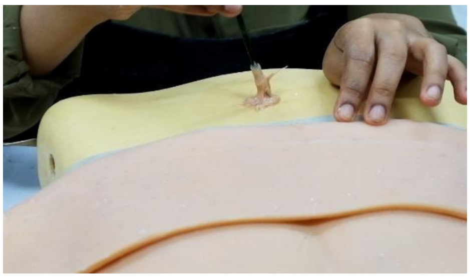


Figure 3.31: Drill coin-sized holes into the mannequin surface (left)

Figure 3.32: Fill in the holes with skin-tone silicone sealant and then abruptly place the skin sheet onto it. Leave it to be well-set for 6-7 hours *When the silicone sealant is all set, it will act as spurs on the skin sheet which are affixed to the mannequin*

Figure 3.33: Paint the plastic mannequin with spray cans

A finished mannequin

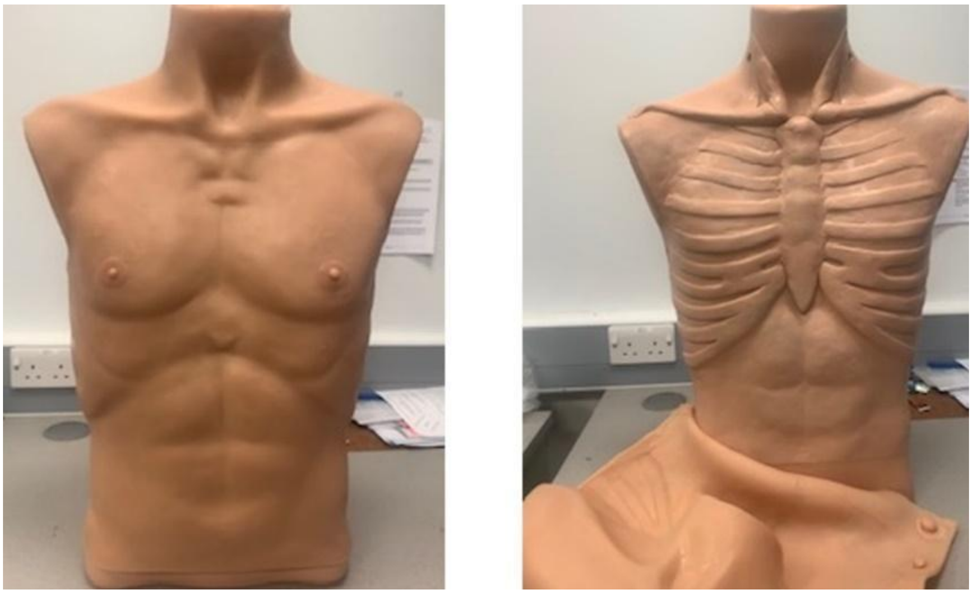


Figure 3.34: A finished male torso mannequin

3.6.1.2 AR application development (hardware and software tools)

This subsection starts with key concepts of hardware and software which were used for developing an AR system within the scope of this thesis—a marker-based AR application. The marker-based approach is under the umbrella of the vision-based tracking systems used among the various studies on AR application (K B, Patil, 2020). Focusing on the simple concept of marker-based AR, the process uses a camera on an input hardware which recognises and captures a marker (or multiple markers), then the computational system recognises that marker(s), and an AR app augments virtual 3D objects onto the captured marker(s). By seeing the physical world through some sort of output devices—wearable display (glasses, head-mounted display) or non-wearable display (smartphone, tablets, or projectors), the user can sense the virtual objects as part of his or her real environment.

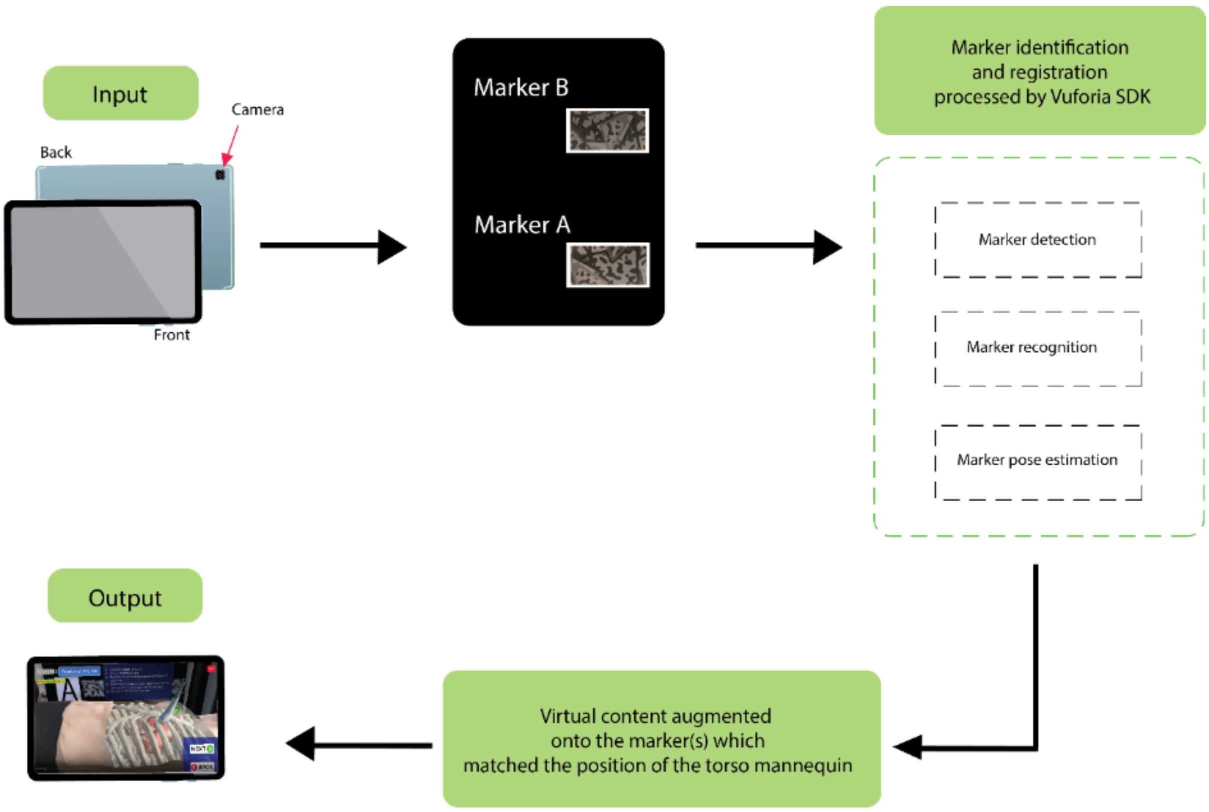


Figure 3.35: Overview of marker recognition in the marker-based AR application

As the Figure 3.35 illustrates, the process starts with the main camera of a tablet—Samsung Galaxy Tab S6 Lite, is used to detect the marker A or marker B, as well as capture, measure the size and orientation of the marker(s). The tablet's camera plays an important role in recognising the marker and visualise AR features/contents associated with the marker(s). In general, the marker can be any form of 2D image—e.g., logo or quick response (QR) code, which is typically made up of black and white geometric patterns or a complex image having multiple layers of basic shapes in order to avoid mixing with a real object and a physical environment.

To keep virtual data matched in the physical world, a tracking system is required in any AR system. The tracking module calculates the relative position of the camera based on accurately detected and recognised markers in the scene. The process started with preparing the two binary (fiducial) markers and then importing them into the Vuforia Engine Developer Portal for creating AR marker database with Vuforia (Figure 3.21).

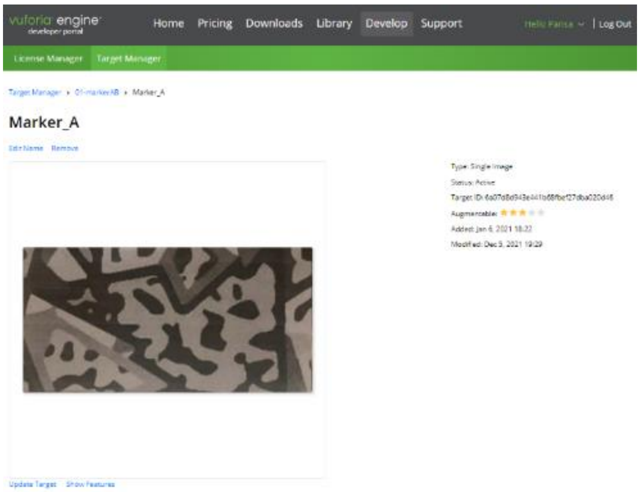


Figure 3.36: Screenshot of uploading an image file as an AR marker on the Vuforia Developer Portal

Vuforia (PTC Inc., Massachusetts, United States) is a cross-platform of software development kit (SDK) that supports the development of augmented reality applications on a wide range of platforms and devices such as smartphones, tablets, and AR headsets (PTC, Inc., 2020). It can operate satisfactorily together with Unity SDK. Vuforia Engine supports robust tracking systems for the building of AR application systems for mobile devices and AR glasses. When Unity can be used to develop interactive content and user interface design for AR development, the technology of Vuforia Engine is to recognise and track 2D images or 3D objects in real time. A development process for authoring mobile AR applications with Unity and Vuforia Engine is presented in Figure 3.22.

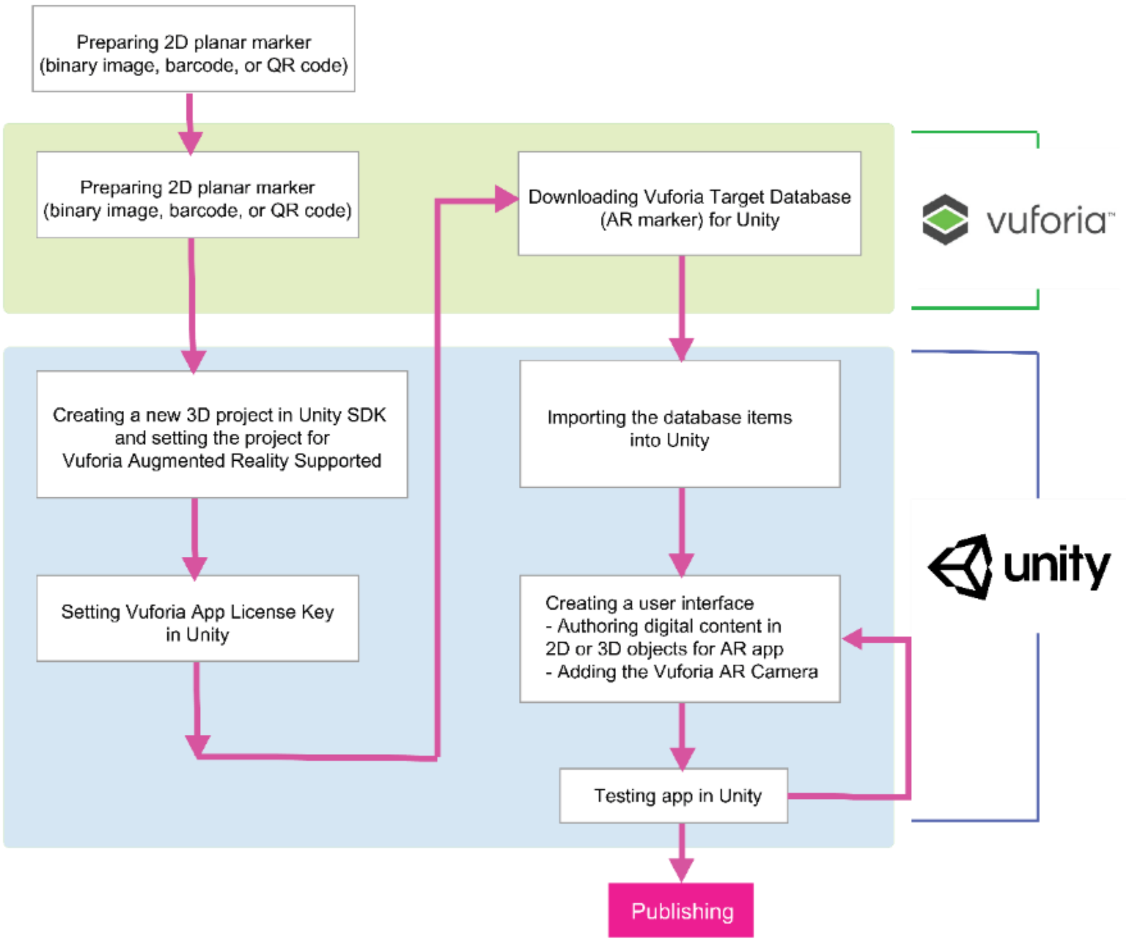


Figure 3.37: Development process of marker-based AR application with Vuforia Engine and Unity SDK

3.6.1.3 AR application development (user interface design and implementation)

As the previous subsections describe the AR authoring tools and basic workflow of marker-based AR application, this subsection focuses on 2D and 3D graphics representing basic TTE which are implemented into the Unity SDK workspace to create the AR application. In order to explore the impact of AR the application on medical trainees' knowledge and satisfaction compared with a learning session with the computer-based multimedia in basic TTE, the user interface of the AR app was developed, aiming at combining a life-size torso mannequin with 3D digital content to simplify the cognitive workload. To create the AR application, the first task was to define how the user's experience will be.

As stated earlier, this study was conducted during the Coronavirus disease of 2019 (COVID-19) global pandemic and hence developed using a mobile-based AR application instead of mixed reality (MR) app equipped with a wearable headset and controllers, to minimise COVID-19 transmission risk during the experiment. Although the mobile AR app may not provide a simulated psychomotor skill relating to TTE examination as planned, it can start to paint a picture for learners about AR technology and visual perception of spatial relationships between surface anatomy, cardiac structures, and methods of handling transducer position for visualising different views of basic TTE.

Mealy (2018) proposed the important factors that should be considered when designing the AR application. First, the comfort zone of learners when they interact with the AR app on a mobile device should be prioritised. In the modern world, most people have become accustomed to use smart devices in their daily life; therefore, they already have the manual dexterity to interact with the screen of a mobile device, including single-finger taps, two-finger pinching (zoom-in and zoom-out), drags, and rotating. In a smartphone/tablet AR experience, a user has to keep a certain distance between his/her position of holding a device and marker(s) to obtain a view into the augmented environment within the device. However, an AR developer or designer should consider the time setting of handheld mobile AR experience, as some present research reported that holding a device too long can induce the user's fatigue.

With that in mind, a marker-board was attached with marker A and marker B provided in the AR environment setting which allows users to tilt up and down at any marker they want. The marker A was installed below the marker B as its UI demonstrates 3D virtual contents regarding the technique of correct placement, holding and manipulation of the ultrasound probe in basic TTE examination to obtain each echocardiographic window. When a user locates a tablet's camera toward the marker A, he/she will be able to see a 3D presentation including a transparent 3D torso model with a ribcage, a transducer probe correlating with each of the echocardiographic planes on the animated heart. 3D virtual data of the marker A was designed to demonstrate a seamless match with the physical torso mannequin. However, the author anticipated that the user may experience hand and arm fatigue during their movement of tilting up and down between the marker A and B. Therefore, an installation of a table and a chair was planned to be set for the comfort of users. They can sit or stand as they feel comfortable for relaxing and rest their arm during AR learning experience.

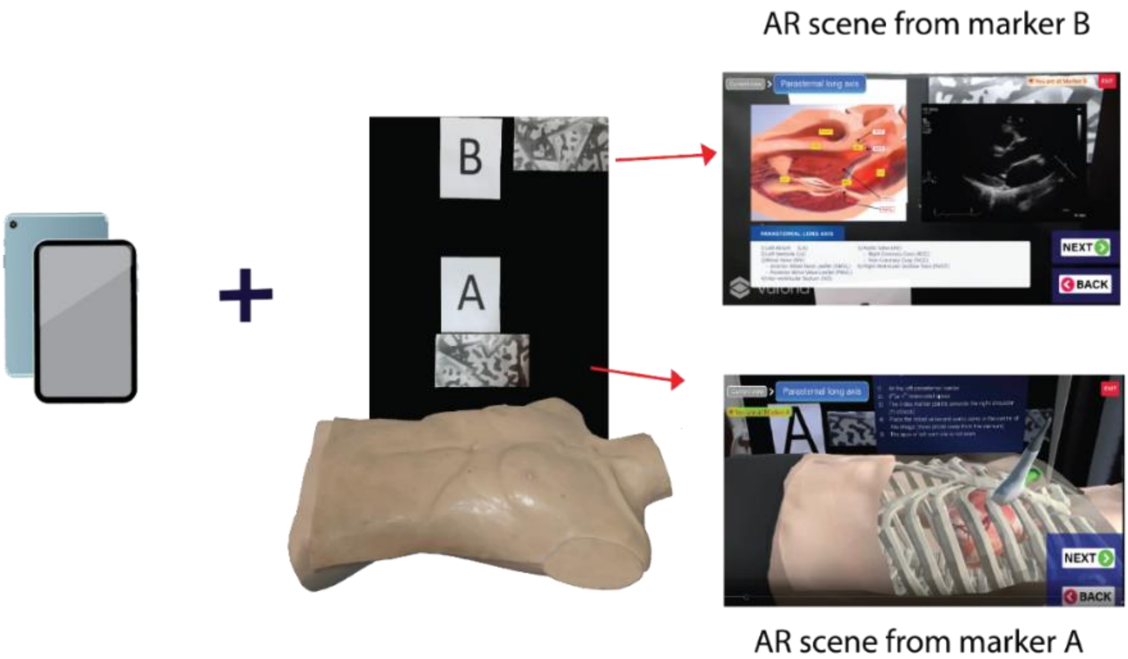


Figure 3.38: Real setting of AR application **(**a tablet, a marker board and a torso mannequin**)**

Second, Mealy (2018) also focuses on the user interface pattern. Although AR technology has superior benefits of interactive digital experience, when compared to the flat layout graphics on computer screen, the AR interface should be designed to have easy navigation, be distinct from the physical user's environment, and avoid expandable and hidden menus (nested structures) as much as possible in the AR space. Functionality of icons and buttons appearing in the UI should give the user a sense of the AR application's purpose and avoid creating unfamiliar 2D icons which may lead to users' misconception or force them to learn an AR system which may not have relevance to them.

With that in mind, the author simplified the UI of the AR app to have only three buttons on the right-hand side. These buttons are 'Exit', 'Next' and 'Back'. Crucial parts of UI are only 3D virtual animated objects and instructional text display. The design process was conducted with an in-depth analysis of the literature on basic TTE education and the author's experience from attending the FICE hands-on workshop, as described in Chapter 3, Section 3.2.1.3 One-day hands-on training workshop. Most of the AR instructional contents are identical with the content as presented in the computer-based multimedia (Section 3.4: The production process of computer-based multimedia).

The authoring process was mainly executed in Unity SDK workspace. All 3D (static and animated) assets—exported from the 3Ds Max software as .FBX files—were uploaded into the Unity game engine. Instructional text displays, icons and buttons were created as vector-based files from Adobe Illustration software. After importing all 2D and 3D assets into the Unity Project, each scene of AR application was developed to set animation, play video of actual TTE scan and provide virtual buttons mode for user interaction (Figure 3.24).

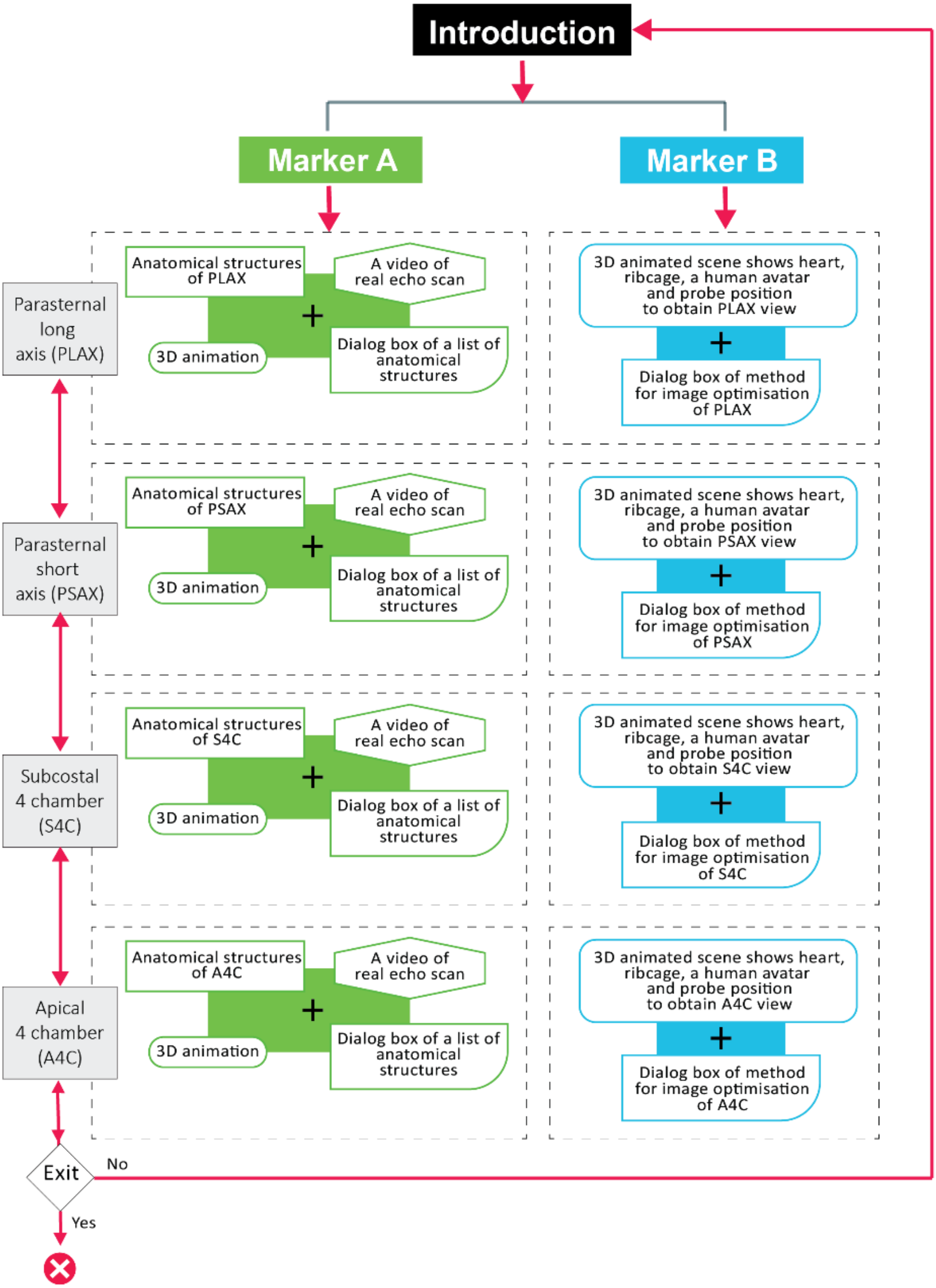
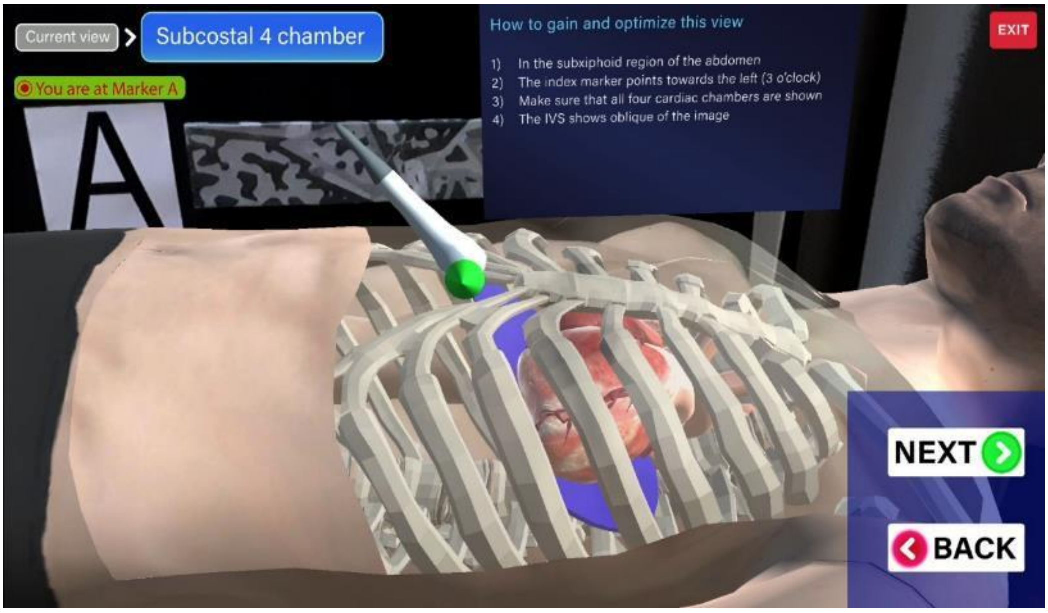


Figure 3.39: User interface flowchart of the mobile-based AR application



(A)

(B)

Figure 3.40: Screenshot of actual AR application for basic TTE**:**

(A**)** image acquisition knowledge for PLAX view obtained from the marker A,

(B**)** anatomical knowledge of PLAX view obtained from the marker B

3.7 The impact of the COVID-19 pandemic on the study outline framework

Time constraints and the ongoing global pandemic of coronavirus disease 2019 (COVID-19) had limited plans for a case study of the research. The development planning of the AR application and computer-based multimedia module were developed after the attendance of the FICE workshop and was approved by the supervisors and the subject matter experts from the Queen Elizabeth Hospital Birmingham at the early stage of PhD research. In the first plan, the author aimed to recruit undergraduate students (at least ten persons) from the College of Engineering and Physical Sciences, University of Birmingham, to be volunteer participants for testing the first version of the computer-based multimedia and AR application. The pilot test of the computer-based multimedia module and AR application was aimed to verify the content and obtaining the initial feedback about the learning experience which essentially simulated the conditions expected in the actual experiment. However, the pilot test did not happen due to the pandemic circumstance.

The COVID-19 pandemic circumstance caused the author to make major changes to the research plan. The target participant was initially designed to be foundation doctors (FY1 or FY2) at the Queen Elizabeth Hospital Birmingham (QEHB) who are interested in the multimedia technology enabling them to gain knowledge about basic TTE. In March 2020, when the UK coronavirus lockdown restrictions were announced, the author decided to alter the plan to conduct the experiment in her home country—Thailand.

In order to maintain the study's objectives, Thai doctors at the Faculty of Medicine Siriraj Hospital (Mahidol University, Thailand) who have a level of profession being equivalent to foundation doctors in NHS system, were recruited instead. Therefore, the ethical review process for conducting the experiment was also changed. Even though the pilot test was cancelled, the author invited three Thai cardiologists to review the proposed learning resources used in this study—the computer-based multimedia and AR application. The feedback given by the Thai experts was mainly positive. Their suggestions regarding the user interface's presentation and interaction of the computer-based multimedia module and AR application were beneficial for developing better versions used for the actual experiment. The next chapter is a full overview of the case study phase—including the ethical review process, the methodology and research instruments, where a further opportunistic sample of residents situated at the Faculty of Medicine Siriraj Hospital engaged with the computer-based multimedia module and AR application.

Chapter 4

Methodology

4.1 Introduction

As previously mentioned, in Section 3.3 Instructional design of interactive learning systems based on the human computer interaction (HCI) and the human-centred design (HCD) fundamentals, the different learning methods—the computer-based multimedia and the marker-based augmented reality application—were developed. This chapter describes the rigorous part of an exploratory case study which is used to investigate the proposed learning media's impact on learners within the context of self-paced learning activities in basic transthoracic echocardiography. The section 4.2 outlines the justification, research questions and objectives. The section 4.3 focuses on research methods including a criterion and an approach for participant recruitment, study design, apparatus and research instruments which were used for data collection.

4.2 Developing case study research questions and objectives

In Chapter 3, the author provided the reason behind why the AR application and the computer-based multimedia module were developed following the case study design for investigating how 3D visual representation fidelity in technology-mediated learning tools for basic TTE affect medical trainees' knowledge improvement and overall satisfaction. The findings from the literature review had raised several interesting aspects which were specifically studied and addressed in Question 2, 3 and 4 following the flowchart in Figure 4.1.

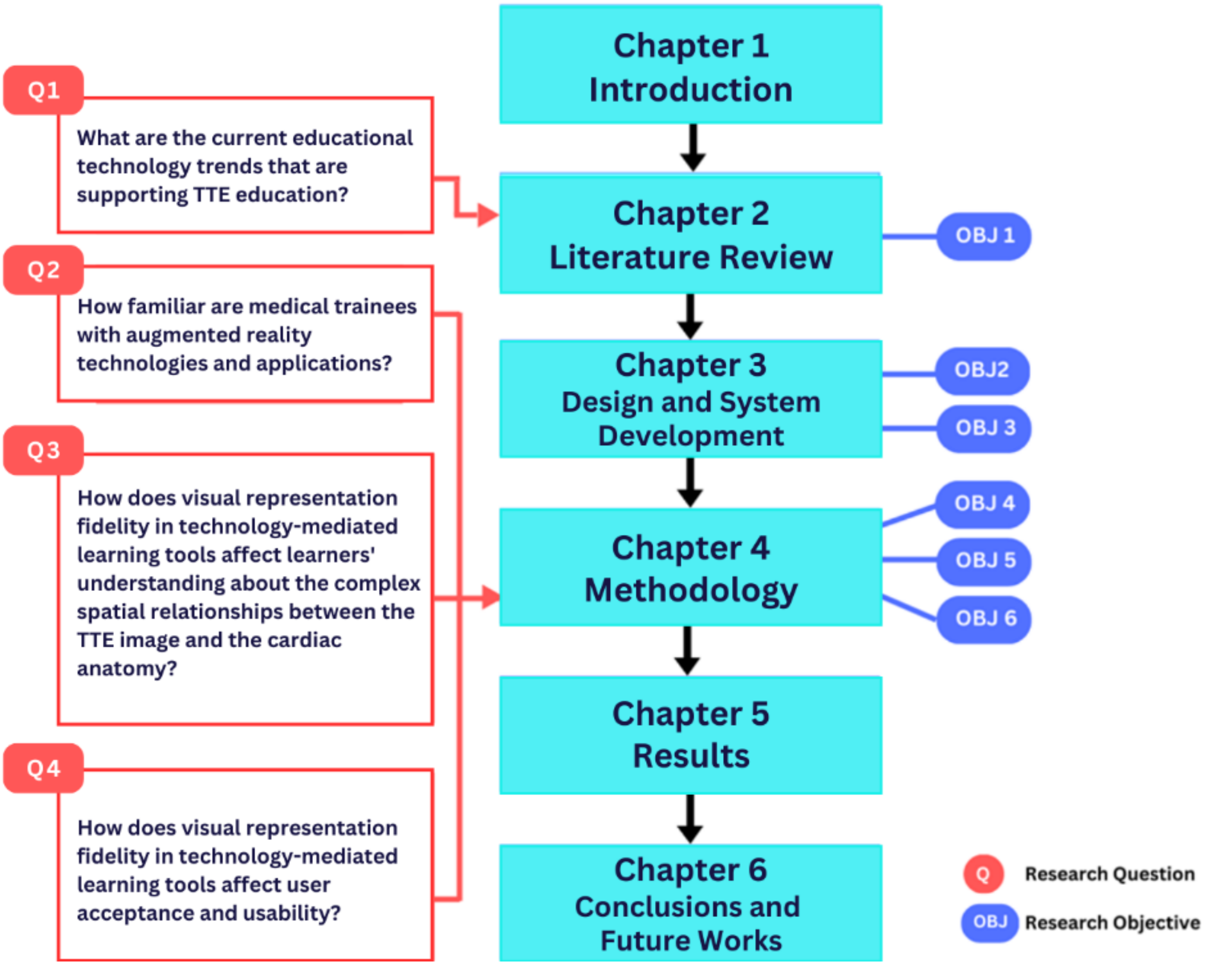


Figure 4.1: Thesis roadmap – Chapter 4

Research question 2

How familiar are medical trainees with augmented reality technologies and applications?

As stated in Chapter 2, new technologies such as augmented reality (AR), virtual reality (VR) and mixed reality (MR) have become a popular trend which dramatically transforms teaching and learning experience in many fields of medical education. However, the so far existing research has rarely investigated how familiar medical students are with the concept of integrating the immersive tech into their learning activities. Furthermore, anecdotal opinions provided by clinical supervisors regarding this topic stated that they had only heard about, but never integrated this type of technology as an educational material in their class. Kalonde and Mousa (2016) investigated in detail what factors influenced instructors' choices to use or not use technology in class. Whilst the personal background and unfamiliarity with novel technologies are the main reason that educators hesitated to apply technological materials/resources in their class; they also reflected that they could not assure it would really impact on students' academic performance and had no indication to help them to select proper technological resources being suitable for their students' characteristics. Therefore, this research question was aimed to provide further evidence as a beginning step in the way to integrate technology into self-paced learning about basic transthoracic echocardiography. Because little is known about this topic, learning experience survey was selected as a research instrument for answering this question. A set of questionnaires used to collect information about the target participants—including their demographic information, recent level of medical training, previous experience towards echocardiography and their familiarisation with augmented reality technology. More details will be provided in Section 4.3 Research Instruments.

<u>Research question 3</u>

How does visual representation fidelity in technology-mediated learning tools affect learners' understanding about the complex spatial relationships between the TTE image and the cardiac anatomy?

According to the literature review, most studies utilised educational technology-mediated tools as part of a blended learning setting in echocardiography education, where medical trainees spend their time in the classroom or the hands-on workshop as well as studying online sessions by themselves. Although it is evident that computer-based multimedia and AR application can be adopted to improve learning experience for students, there is a lack of study focused on how 3D visual presentation and interactive features in these learning media helps medical trainees to enhance their own knowledge construction in echocardiography.

Therefore, this research focused on medical trainees' knowledge improvement of basic TTE which is affected by learning experiences with two different types of media tools: computer-based multimedia (lower visual presentation fidelity) versus AR application (higher visual presentation fidelity). As part of the study, the evaluation knowledge system was employed. An online interactive test (20 multiple-choice questions) was developed and used for registering the participants' knowledge change between pre-test (before self-learning sessions) and post-test (after self-learning sessions). More details will be provided in Section 4.3 Research Instruments.

<u>Research question 4</u>

How does visual representation fidelity in technology-mediated learning tools affect user acceptance and usability?

In recent years, there has been a trend among medical schools or educators to study the potential of technology-assisted education. The findings of several studies pointed out that technology-enhanced learning, when optimised, is effective for improving students' learning outcomes in many ways, such as knowledge improvement, increased engagement during class, or enhancing clinical skill retention (McCoy, Lewis and Dalton, 2016). However, with that in mind, it is noticeable that there is a lack of reports studying in detail how the benefits of using technological media for self-study impact on usability, students' enjoyment, and satisfaction (Jwayyed et al., 2011). According to Chapter 2, the majority of studies based on the specialty of echocardiography education attempted to measure gains in knowledge or skills. Those studies sought to directly compare technology-assisted learning session to traditional instructor-led teaching. Their findings showed that the effectiveness of technology-assisted learning was equal or superior to traditional lecture methods, but the author did not find any study which directly compared a novel learning technological medium to another existing technology. Hence, this research question aims to initiate the investigation of user feedback on the usability of two proposed educational media—augmented reality application and computer-based multimedia used for self-paced learning. To answer this question, this study adopted the System Usability Scale (SUS), the Standardized User Experience Percentile Rank Questionnaire (SUPR-Q) and the Technology Acceptance Model (TAM) for measuring participants' feedback around several components of usability and subjective satisfaction referring to how pleasant the proposed learning tools are to use. More details will be provided in Section 4.3 Research Instruments.

In this thesis, the exploratory case study was set to test research null hypotheses as follows.

1) Determine whether the use of 3D visualisation delivered through two different technologies (computer-based multimedia and AR application) really help improve understanding of basic TTE. The null hypothesis is that participants cannot show significantly greater gains in scores in terms of comparing post-test and pre-test scores.

2) Determine whether the participants learn better from the AR application than they do from the computer-based multimedia. The null hypothesis is that there are no statistically significant differences in learners' knowledge improvement when they receive two different instructional interventions: computer-based multimedia and AR application.

3) Determine whether participants prefer learning with AR application over with computer-based multimedia. The null hypothesis is that the participants' feedbacks in the point of usability attributes and subjective satisfaction towards both learning media are not significantly different.

4.3 Method

4.3.1 Participants: eligibility and criteria

Discussion with the clinical supervisors from the Queen Elizabeth Hospital Birmingham (QEHB) contributed to the criteria for recruiting participants. They suggested that newly qualified doctors undertaking the Foundation Training programme—a two-year, general postgraduate medical training programme bridging between undergraduate medical degree and general/specialist practice training (UK Foundation Programme, 2021)—are suitable and eligible for this study. After completing medical school, entry to the foundation training is the first step for the newly graduated doctors to practise in basic clinical skills, essential skills required for acute care management, as well as communication skills and teamworking (UK Foundation Programme, 2021). Therefore, early implementation of basic TTE training seems to be beneficial for foundation (junior) doctors with no previous echocardiography experience assumed.

However, the abovementioned eligible criteria had to change due to the COVID-19 pandemic circumstance leading to change in research site for conducting the experiment in the author's home country—Thailand. In order to maintain the study's objectives, Thai residents at the Faculty of Medicine Siriraj Hospital (Mahidol University, Thailand) who have a level of profession being equivalent to foundation doctors in NHS system, were recruited instead.

4.3.2 Participants: sample size estimation

Determining the proper sample size is a critical step of planning research protocol to keep the value of statistical power and lead to the chance assuring the study is valid (Suresh and Chandrashekara, 2012). In this PhD study, sample size was calculated before data collection based on information from a previous study. The author investigated a number of previous comparative studies related to an educational experiment in assessing the effectiveness of learning technologies used for echocardiography education. A study from Ogilvie et al. (2014) was selected as a benchmark because it shared some similar characteristics with this PhD study. First, research participants were novice medical trainees who had no experience of transthoracic or transoesophageal echocardiography (TTE or TOE). Second, participants were randomly assigned into two groups which exposed to different learning activities. Last, their primary research objective focused on how different learning design features impact upon knowledge construction and student satisfaction. Ogilvie et al. (2014) reported that, after comparing pre- and post- test, the trainees of the simulator group (N=25) had significantly higher knowledge scores than the other group which had been exposed to conventional lecture method (N=26).

The author started with adopting some values from Ogilvie et al. (2014) research for calculating the sample size. Values which were used were median, (lowest-highest value of the range): 60, (40-95) in the simulator group, and 50, (15-90) in the conventional (control) group. The next step was to calculate mean value ($\overline{x}$), standard deviation (S.D.), effect size (Cohen's d), these values were calculated on two websites (Lowry, 2019; Stangroom, 2019). The results were as follows.

- Simulator group: Mean ($\bar{x}$) = 63.75, S.D = 13.75
- Traditional learning (control) group: Mean ($\bar{x}$) = 50, S.D = 18.75
- Cohen's d = 0.76

These mentioned values were then used for calculating the final sample size based on a significant level (α = 0.05) and power of the test (80%) by the G*Power software (Heinrich-Heine-Universität Düsseldorf, 2021). The result showed that this study should recruit 58 subjects (29 in each group).

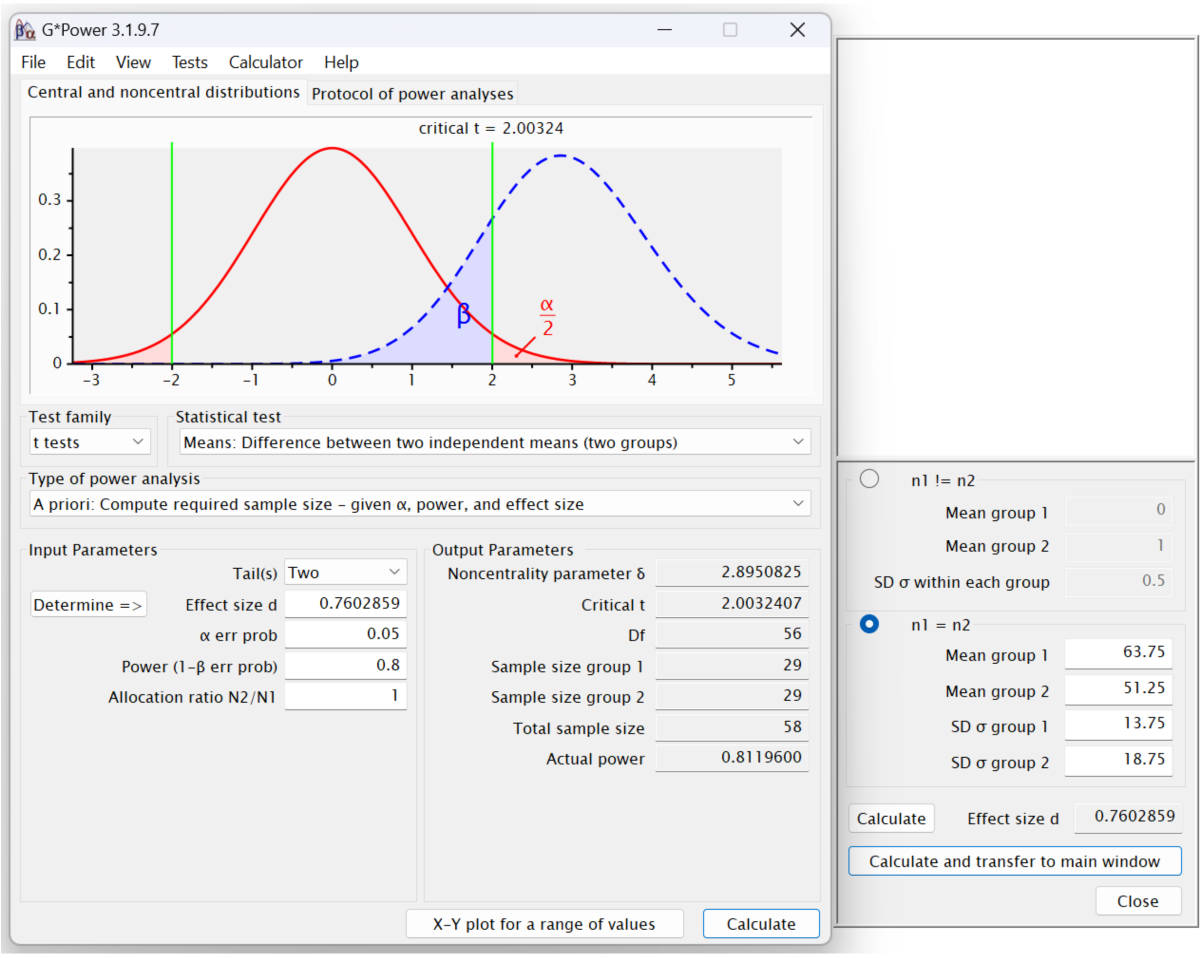


Figure 4.2: Calculation of the sample size with the G*Power software (Heinrich-Heine-Universität Düsseldorf, 2021).

4.3.3 Participants: Recruitment

Potential participants were voluntarily recruited using an opportunistic (availability) approach by direct contact with a resident student representative within the Department of Medicine, Faculty of Medicine Siriraj Hospital, Thailand. Ethical approval was granted from the Siriraj Institutional Review Board (Siriraj IRB) within the Faculty of Medicine Siriraj Hospital, Mahidol University, Thailand.

4.3.4 Research design

Voluntary participants were provided with the participant information sheet (Appendix B) detailing the experimental procedure. Next, they were asked to complete the consent form (Appendix C) that detailed their right to withdraw and assured that their personal data would be anonymised and confidential. Finally, the participants were asked to fill in a paper-based questionnaire (Appendix D), which identifies each participant's background as well as their skill and experience with echocardiography examination and their experience with the different technologies used as learning resources. The next process is the group assignment for participants prior to an intervention. The participants joining the study are sequentially assigned one to each group. For example, the first participant is assigned to Group A—first learning session with multimedia module, and the second participant is assigned to Group B—first learning session with AR application. They were also informed which group they belonged to.

The first phase of the intervention was aimed at assessing residents' knowledge gain in association with self-learning with either computer-based multimedia (group A) or AR application (group B). Participants were asked to complete an interactive MCQ pre-test of basic knowledge of TTE. The test module consisted of 20 multiple-choice questions which were developed under the guidance and review by the clinical supervisors from the Queen Elizabeth Hospital Birmingham (QEHB). The pre-test and the post-test modules were similar, although not identical.

After completing the interactive pre-test, the participants in group A were assigned to learn with the computer-based multimedia module while the participants in group B were provided with the marker-based AR application as their first self-paced learning session. Each learning session lasted for 20 minutes. Residents were also asked to complete the post-test evaluation at the end of this session. All objective performance data (pre and post-test scores, time completion of the tests) were recorded automatically from the system (more details in Subsection 4.3.5) and was output as a log file which could be input into a spreadsheet for analysis.

The second session was aimed at exploring the residents' ratings of the AR application and the computer-based multimedia's usability and their satisfaction with these learning tools. This session, lasted for 15 minutes, participants were assigned to the other arm of learning tool—subjects in group A were asked to look into the AR application while group B investigated the computer-based multimedia. Upon completion of the procedure, the participants were requested to complete a set of paper-based questionnaires about subjective measures—usability and satisfaction. All mentioned procedures are presented below, Figure 4.3.

A total of 46 participants were voluntarily recruited, including 27 male and 19 female doctors in residency training programme in internal medicine (year 1, 2, or 3).

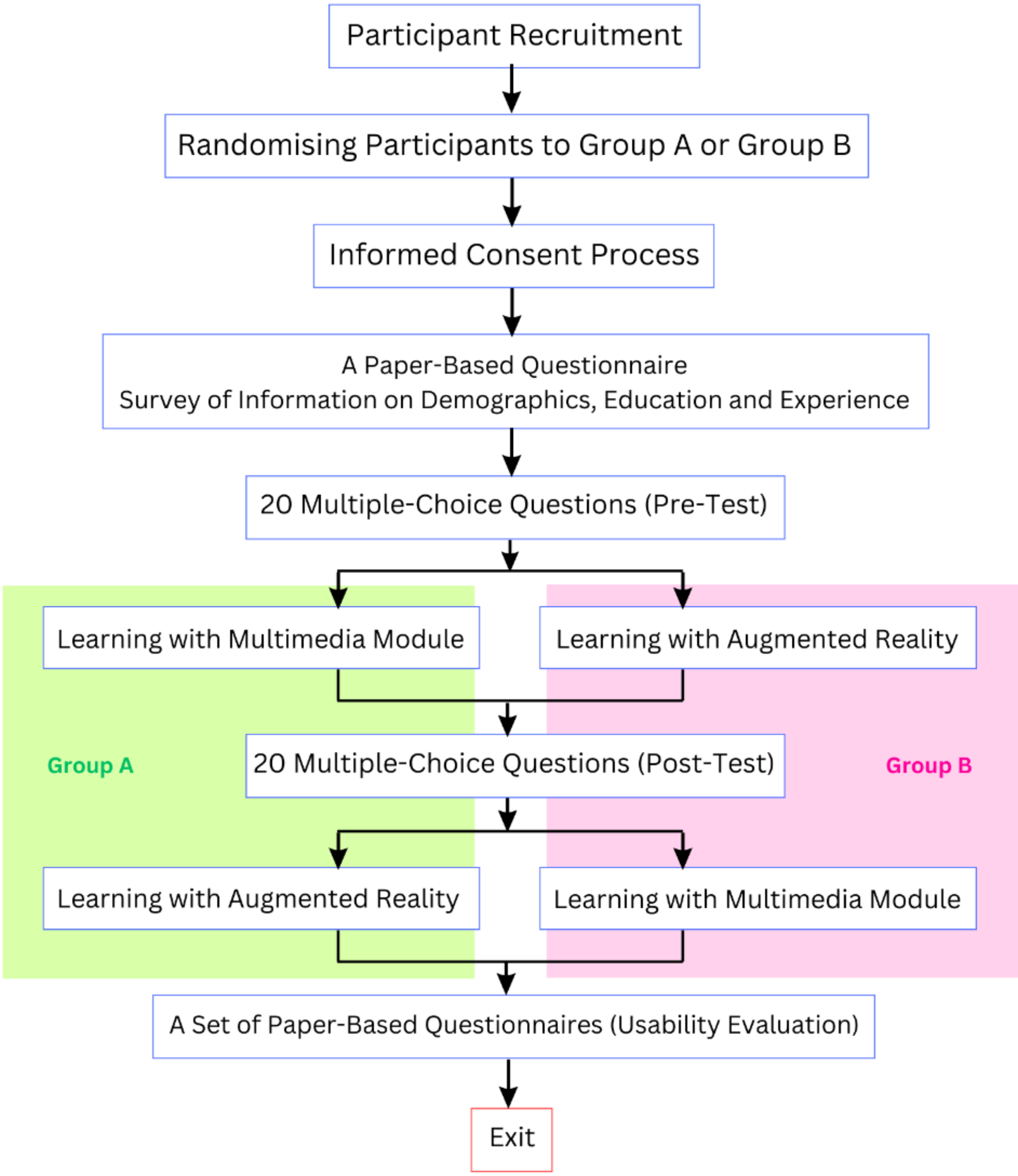


Figure 4.3: Study flowchart

4.3.5 Apparatus and research instruments

The research site was set at the office of Internal Medicine, Department of Medicine, Faculty of Medicine Siriraj Hospital, Thailand. Prior to the intervention, residents were provided with a paper-based package containing a participant information sheet, a consent form and a baseline survey of demographics, education, and experience. A laptop computer was employed for pre-test and post-test tasks evaluating students' knowledge about basic TTE before and after the first learning session.

Interactive pre- and post- test modules were developed as research instruments for determining the participants' knowledge gain after receiving the education. As earlier mentioned, after obtaining the consent for voluntary participation, the residents were asked to take the pre-test containing 20 questions on basic TTE, and the same 20 questions were provided at the end of the second self-paced learning session as the post-test questionnaire to assess the effectiveness of the technological learning media on the knowledge gain.

The author used Socrative (Socrative, 2020) for creating the pre-test and post-test modules. Socrative is a cloud-based (Internet) Student Response System (SRS) which is accessible for free on its site. It is widely accepted that Socrative software can provide many positive benefits for assessed tests (both as a formative and summative learning tool) including allowing users to easily create their own quizzes in various types of questions—multiple-choice, true/false or short-answer, and offering accessibility on various hardware: desktops, smartphones, and tablets. (Pryke, 2020).

Once creating a free account, the author developed the pre-and post-test modules within a given public room. The public room is an online space automatically provided for each developer (teacher) account where teachers and their students can access simultaneously, both in and out of the formal classroom environment. Within the given public room, the author imported the prepared components (text, images and videos) of 20 multiple-choice questions about basic TTE to create test modules—an example of creator dashboard provided in Figure 4.4. All questions of the post-test were similar to that of the pre-test but shuffled in order. A full list of 20 questions is designed to assess knowledge and understanding in basic TTE—physics of ultrasound and image optimisation, and anatomy and basic windows—as shown in Appendix D: Multiple-choice questions for basic transthoracic echocardiography.

When doing the test, voluntary participants did not need to create their own accounts. The author invited them via a URL into the public room to access test modules. In order to track participants' instant formative feedback, they were requested to enter their personal name before starting the test. Whilst participants were completing the interactive MCQ—an example of test interface shown in Figure 4.5, the author could monitor their answers in real-time. Participants were asked to complete each test within 20 minutes. Time to complete the test was recorded by the author. Another advantageous feature of Socrative is a report section which helped this study in data collection. The author could download an Excel spreadsheet with data on overall performance. Individual participant reports were also available to download in PDF format. Aggregate and individual results could also be used in the process of statistical analysis.

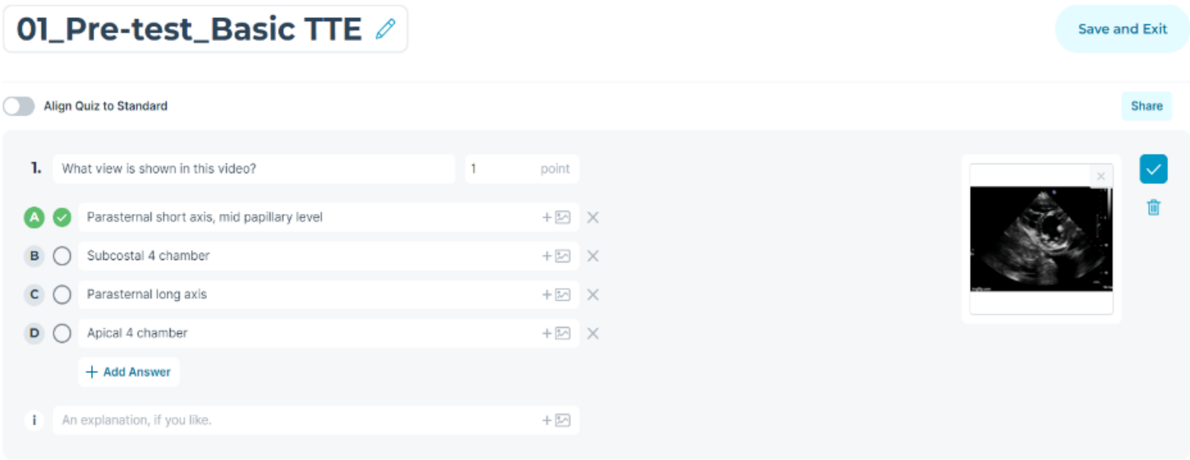


Figure 4.4: A screenshot of Socrative software via Teacher Login: creating a quiz (pre-test)

Text not intended to be read

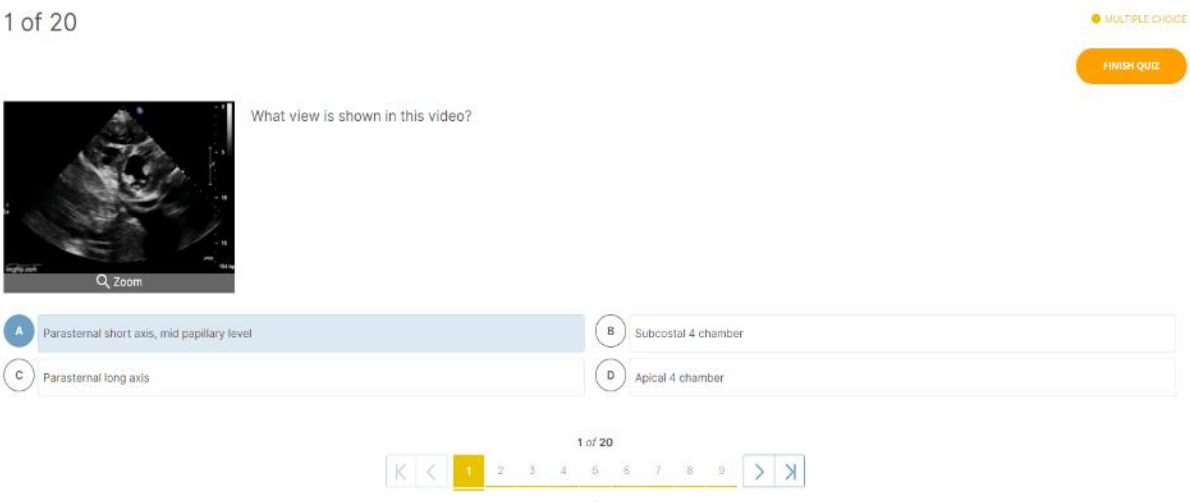


Figure 4.5: A screenshot of Socrative software via Student Login: answering a quiz (pre-test)

Text not intended to be read

Participants could experience a self-directed computer-based multimedia learning session delivered via the laptop as well. Figure 4.6 illustrates the way a participant interacts with the laptop computer; the left panel shows the participant completing the pre-test while the right panel depicts the participant experience in self-paced computer-based multimedia learning session.

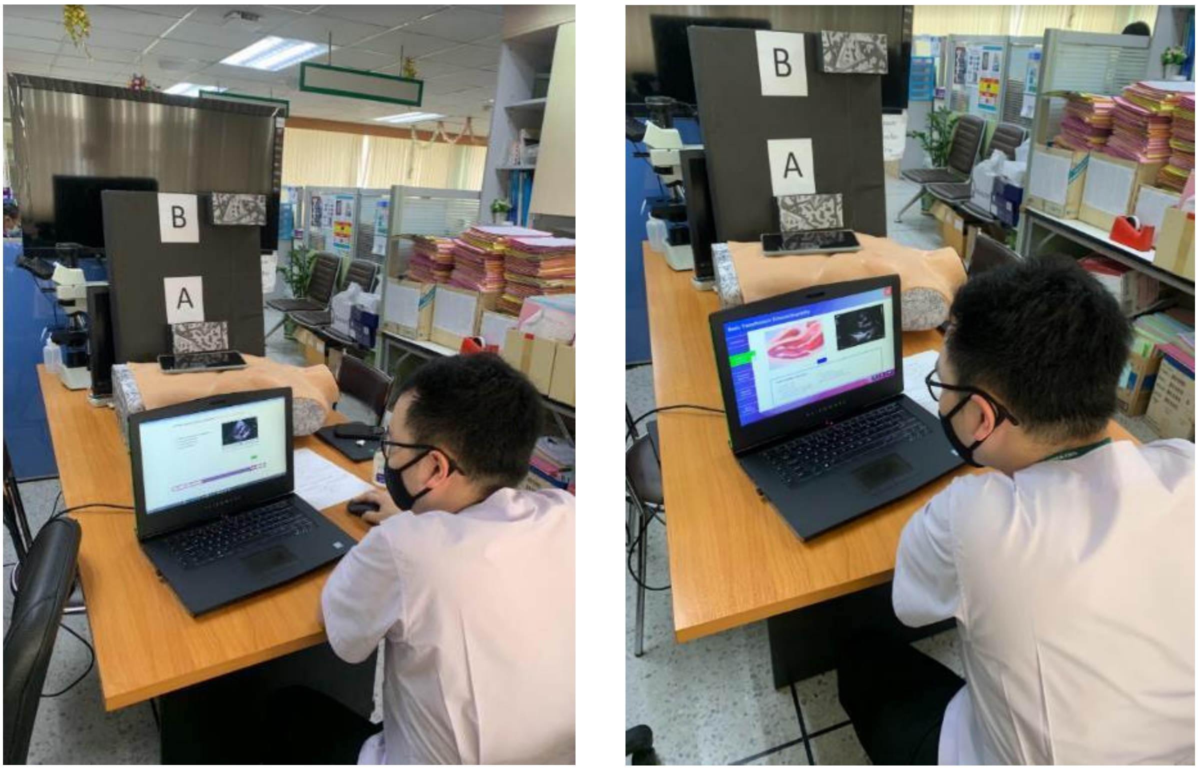


Figure 4.6: Pre-test session (left), self-paced computer-based multimedia learning session (right)

The apparatus of the AR application system was set as shown in Figure 3.38. The system allowed the participant to visualise, navigate and interact with the virtual content using a tablet. For the AR environment, participants were able to see real-world objects and the augmented content was precisely overlaid onto a torso mannequin and a marker-board. Figure 4.7 illustrates the participant interacting with the tablet.

In addition to objective measurement, a subjective evaluation was also carried out. Participants' experiences and perception regarding the usability of the proposed learning tools were evaluated using a set of questionnaires (Appendix F) containing two published instruments—the System Usability Scale (SUS), the Standardized User Experience Percentile Rank Questionnaire (SUPR-Q), the Technology Acceptance Model (TAM), and an open-ended question.

The international Organization for Standardization (ISO)—a network, non-governmental, organisation who has developed over 24,197 international standards serving the requirements of a wide range of businesses and industries—described concepts and definitions in the definition of usability (ISO, 2018). As described by the *ISO 9241-11: 2018(en) Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts*, the term 'usability' encompasses a quality attribute that evaluate user friendliness of a product or service. Usability can be relevant to:

- regular ongoing use, to enable users to achieve their goals effectively, efficiently and with satisfaction;
- learning, to enable new users to be become effective, efficient and satisfied when starting to use a system, product or service;
- infrequent use, to enable users to be effective, efficient and satisfied, with the system on each reuse;
- use by people with the widest range of capabilities;
- minimizing the risk and the undesirable consequences of use errors; and

- maintenance, in that it enables maintenance tasks to be completed effectively, efficiently and with satisfaction (ISO, 2018).

The System Usability Scale (SUS) is a questionnaire developed by John Brooke (Brooke,1996) which has been widely used to evaluate the usability of services and products. This questionnaire is one of the popular tools for usability evaluation as it can be implemented easily and in less time. In general, the SUS questionnaire contains 10 questions using 5-point Likert scale ranging from “Strongly Disagree” to “Strongly Agree”. The SUS score is numbered between 0 and 100. The average SUS score, based on over 500 studies that tested systems and application using the SUS questionnaire, is 68. Thus, a SUS score above 68 is considered acceptable and good (Sauro, 2011; Brooke, 2013). The author also adopted the Standardized User Experience Percentile Rank Questionnaire (SUPR-Q) as another instrument for evaluating additional aspects for subjective measurement.

The SUPR-Q, developed by Jeff Sauro, contains 8 questions scored on a 5-point Likert scale from “Strongly Disagree” to Strongly Agree. The results of SUPR-Q questionnaire can reflect users’ perception around several components including usability, creditability, loyalty, and appearance (Sauro, 2015; TryMyUI, 2021).

In this thesis, an evaluation questionnaire of learners’ acceptance and intention to use the proposed learning media is based on the technology acceptance model (TAM) (Davis, 1989). The TAM model is one of the common tools to survey user feedback regarding the impact of subjective factors on users’ behaviour and their decision to accept and use a technological system. The original TAM model is built on two types of variables—the independent variables which includes perceived usefulness (PU) and perceived ease of use

(PEOU), and the dependent variables which includes behavioural intention to use and actual system use. Recently, the TAM model has been expanded and modernised to be various models including the TAM 2 (Venkatesh and Davis, 2000), the unified theory of acceptance and use of technology (or UTAUT, Venkatesh et al. 2003), and the TAM 3 (Venkatesh and Bala 2008). This thesis employed the original TAM model by Davis (1989).

The qualitative part of the evaluation survey also included one open-ended question asking for participants' personal suggestions and comments for how the computer-based multimedia and the AR application may be improved in the future. Each participant was asked to complete this set of questionnaires before exiting the study, as shown in Figure 4.8.

Figure 4.7: Self-paced learning session with AR application

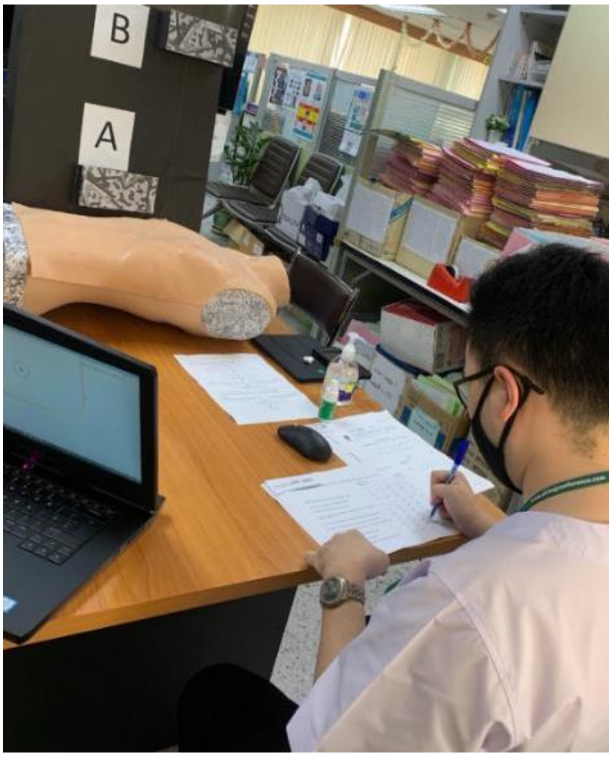


Figure 4.8: Completing the set of questionnaires for subjective measurement

4.4 Summary

This chapter has provided the overview, details, and the justification behind the design and features of the experiment based on the research aims. The effectiveness of the proposed different learning technologies was investigated in two aspects: objective and subjective measurement. The objective measure focused on the improvement of basic TTE knowledge in the internal medicine residents after their learning experiences with two different technologies assessed through the method of pre-and post-test design. Whereas the final measurement was based on the usability attributes, satisfaction, attitudes and opinions of the users towards two learning medias which would be quantified and analysed based on the psychological instruments—the System Usability Scale (SUS), the Standardized User

Experience Percentile Rank Questionnaire (SUPR-Q), the Technology Acceptance Model (TAM) and an open-ended question. Data analysis and interpretation of both objective and subjective measurements present in the next chapter.

Chapter 5

Results

5.1 Introduction

Most participants successfully responded to interactive MCQ modules and questionnaires. Two dependent variables were measured in the experiment, and they were classified as objective and subjective measures. Participant's performance in increased knowledge was assessed using the interactive MCQ pre- and post-test modules, whereas three questionnaires were used for subjective measurements based on the participants' background, experience, and their usability feedback towards two learning methods. The following sections elaborate all details with respect to a proposed sequence of the experiment following the methodology described in Chapter 4.

5.2 Descriptive statistics of participant demographic and background characteristics

Baseline demographics and background characteristics of respondents were collected from the questionnaire survey (Appendix C). The study was conducted during February to August in 2020 at the Department of Internal Medicine, Faculty of Medicine Siriraj Hospital, Thailand. Due to COVID-19 circumstance, the recruitment of participants was difficult to reach the calculated sample size—as stated in subsection 4.3.2. Hence, the researcher had to use a convenience sample of internal medicine residents who voluntarily joined the study. A total of 46 participants were recruited including 27 male and 19 female full-time residents in internal medicine—Year 1 (N = 25, 54%), Year 2 (N = 16, 35%), and Year 3 (N = 5, 11%)—at the Faculty Medicine Siriraj Hospital with a mean age of 28 and a standard deviation of 1.08. With respect to background and experience in echocardiography, most respondents (N = 43, 95.5%) pointed that they had some experience of performing an ultrasound examination (e.g., lung, pregnancy, or abdominal) whilst only three participants (6.5%) had never performed ultrasound exams. Highlighting on echocardiography, 22 (48%) participants stated that they never performed echocardiography exams on their own but learned by observing others in clinical routine. 15 (33%) participants had executed echo examination on their own, whereas only 9 (19%) of the residents had no experience with echocardiography before the experiment.

This part of the survey also had a question on perspectives of participants towards how important echocardiography competency is for their career path. Their responses were based on the five-point Likert scale, ranging from “Not important” on one pole to “Very important” on the other. Although the Likert scale generally shows as the numerical value (1-5). The length of the cells is determined as depicted in Table 5.1.

Table 5.1: Qualitative interpretation of 5-point Likert scale measurements

Numerical scale	Mean descriptive equivalent
1	Not important
2	Slightly important
3	Neutral
4	Important
5	Very important

SPSS statistical software version 28.0 was used to analyse the descriptive statistics including percentage, mean, standard deviation, and frequencies. As a result, the majority of participants thought that being competent in echocardiography is very important to their career—the mean value and the standard deviation value presented as 4.35 ± 0.70 (x ± SD). More details are represented in Table 5.2.

Table 5.2: Descriptive statistics on the participants' attitude focusing on the importance of echocardiography skill towards their career path

Likert scale description	Frequency	Percentage	Mean	Std. Deviation
Not important	-	-		
Slightly important	2	4.3		
Neutral	-	-	4.35	.706
Important	24	52.2		
Very important	20	43.5		

Another aspect of this survey was the participants' experience and their perception towards the augmented reality (AR) technology. As stated in previous chapters, unlike other mainstream educational tools—e.g., textbooks, websites, videos, etc.—AR is a novel technology which has gained popularity for educational use in recent years. Thus, it was interesting to investigate whether the participants had ever used or become experienced with

AR technology or not. The choices proposed were “I have never heard of it”, “I have heard the word, but do not know what it is”, “I know it”, or “I know it well, and have experience with it.” Prior to the study, 54.3% of residents (N = 25) stated that they only ever heard the word of “AR” but did not know exactly what it is, whereas 17 participants (37%) had never heard of AR technology and had no idea about it. Only 4 residents (8.7%) confirmed that they really knew the definition and concept of the AR technology, and none of the participants had ever experienced with AR application.

5.3 Analysis of pre-test and post-test performance

Quantitative data (test scores) were automatically collected throughout the experiment and recorded in the report generated by Socrative. These data were imported into the SPSS statistical software version 28.0 for analysis. Pre-test and post-test scores of both groups (group A: learning with computer-based multimedia module, and group B: learning with AR application) were analysed to examine the effectiveness of the learning modules. Means were presented in a standardized format that displayed the mean value followed by the standard deviation value (M = x ± SD). The mean was presented with two decimal places. There are three main findings highlighted in subsections below.

5.3.1 Testing of participant’s background knowledge

This testing was executed for investigating whether sample selection bias occurred and assuring the difference of gain scores between groups caused by the independent variables under investigation, computer-based multimedia versus AR application. The pre-test scores obtained by the residents for both groups were compared and analysed using independent sample t-test. As presented in Table 5.3, the t-test comparison showed no significant differences in the pre-test scores of group A and group B (t = -.33, p = .74).

Table 5.3: Results of independent sample t-test for pre-test of both groups

Test	N	Mean	Std. Deviation	t	P
A-Pretest	23	13.26	4.16	-.33	.74
B-Pretest	23	13.61	2.84		

5.3.2 The effectiveness of learning technologies on knowledge gain

Objective data, the gain in scores between post-test and pre-test for both groups, were analysed using a one-way analysis of variance (ANOVA). The one-way ANOVA is used to determine whether there are any statistically significant differences between the means between independent groups (Lund Research Ltd, 2018). Across all ANOVA analyses, a p-value of p = 0.05 was used as a criterion for statistical significance.

Table 5.4: Descriptive statistics on pre- and post-test scores for both experimental groups

Group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A-Pretest	23	13.26	4.16	.87	11.46	15.06	6	20
A-Posttest	23	18.87	1.39	.29	18.27	19.47	14	20
B-Pretest	23	13.61	2.84	.59	12.38	14.84	7	18
B-Posttest	23	18.87	1.39	.29	18.27	19.47	15	20
Total	92	16.15	3.81	.40	15.36	16.94	6	20

Table 5.5: Results of ANOVA for pre- and post-test scores

Test	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	680.74	3	226.91	31.05	<.001
Within Groups	643.13	88	7.30		
Total	1328.87	91			

Table 5.6: Results of multiple comparisons (post hoc testing) on test scores

Group (I)	Group (J)	Mean Difference (I-J)	Std.Error	Sig	95% Confidence Interval	
					Lower Bound	Upper Bound
A-Pretest	A-Posttest	-5.609*	.914	<.001	-8.20	-3.01
	B-Pretest	.348	1.050	1.000	-3.26	2.56
	B-Posttest	-5.609*	.914	<.001	-8.20	-3.01
A-Posttest	A-Pretest	5.609*	.914	<.001	3.01	8.20
	B-Pretest	5.261*	.660	<.001	3.41	7.11
	B-Posttest	.000	.410	1.000	-1.13	1.13
B-Pretest	A-Pretest	.348	1.050	1.000	-2.56	3.26
	A-Posttest	-5.261*	.660	<.001	-7.11	-3.41
	B-Posttest	-5.261*	.660	<.001	-7.11	-3.41
B-Posttest	A-Pretest	5.609*	.914	<.001	3.01	8.20
	A-Posttest	.000	.410	1.000	-1.13	1.13
	B-Pretest	5.261*	.660	<.001	3.41	7.11

* The mean difference is significant at the 0.05 level.

As observed from Table 5.4 and Table 5.5, there was a significant difference effect of learning interventions on gain scores at the $p<.05$ level for the three conditions [$F(3,88) = 31.05$, $p = <.001$]. This significant difference could be between any or all of conditions in the experiment. Therefore, post hoc comparisons using Tamhane's T2 were required for determining difference between each pair of means. Data visualisation of post hoc test is illustrated in Table 5.6.

Gain scores were analysed for both groups as illustrated in Figure 5.1. For group A of 23 residents learning with computer-based multimedia, there was a statistically significant improvement in cognitive knowledge by comparing the pre-test and post-test means (13.26 ± 4.16 versus 18.87 ± 1.39, $p = <.001$), whereas 23 participants of group B also showed their knowledge improvement through the gain scores as well (13.61 ± 2.84 versus 18.87 ± 1.39, $p = <.001$). Therefore, the null hypothesis of the first primary aim that participants cannot show significantly greater gains in scores in terms of comparing post-test and pre-test scores is rejected.

Tamhane's T2 post hoc tests showed that there was no significant difference of knowledge improvement, by comparing the means of post-test scores, between group A and group B (mean difference = 0.00, $p = 1.00$). Hence, the null hypothesis of the second primary aim—the AR application has no greater effect on increasing participants knowledge as they cannot perform significantly better on post-test questions after learning session with the AR application than they do on post-test questions after learning experience with the computer-based multimedia—is accepted.

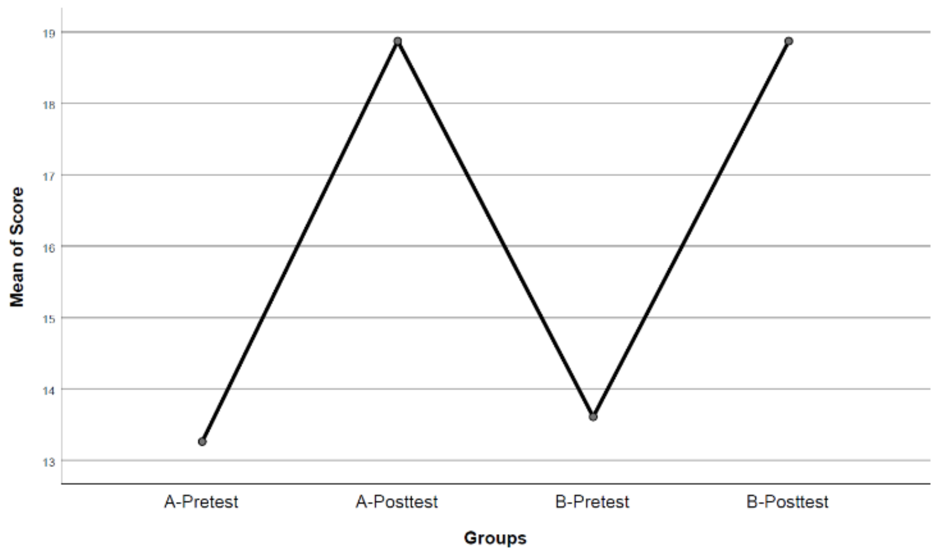


Figure 5.1: Mean of pre- and post-test scores in both groups of participants

5.3.3 Test completion times analysis

According to the above results, no statistical difference in knowledge gain was found between two different experimental groups. This led the author to exploit a time-based measurement as another independent variable for investigating the effectiveness of proposed learning technologies. The completion time in this study means the time which the participants took for completing pre-test or post-test. The completion times of both experimental groups were manually recorded by the author. Comparisons were performed using one-way ANOVA followed by post hoc test using Bonferroni correction.

Table 5.7: Descriptive statistics on test completion time for both experimental groups

Group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A-Pretest	23	7.56	2.36	.49	6.54	8.58	3.67	12.83
A-Posttest	23	7.21	2.38	.50	6.18	8.24	3.70	12.25
B-Pretest	23	9.74	2.80	.58	8.53	10.95	4.24	14.50
B-Posttest	23	7.03	1.43	.30	6.40	7.65	4.55	11.87
Total	92	7.88	2.51	.26	7.36	8.40	3.67	14.50

Table 5.8: Results of ANOVA for test completion time

Test	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	108.58	3	36.19	6.85	<.001
Within Groups	464.72	88	5.28		
Total	573.31	91			

Table 5.9 Results of multiple comparisons (post hoc testing) on test completion time

Group (I)	Group (J)	Mean Difference (I-J)	Std.Error	Sig	95% Confidence Interval	
					Lower Bound	Upper Bound
A-Pretest	A-Posttest	.35087	.67765	1.000	-1.4783	2.1800
	B-Pretest	-2.17478*	.67765	.011	-4.0039	-.3457
	B-Posttest	.53348	.67765	1.000	-1.2957	2.3626
A-Posttest	A-Pretest	-.35087	.67765	1.000	-2.1800	1.4783
	B-Pretest	-2.52565*	.67765	.002	-4.3548	-.6965
	B-Posttest	.18261	.67765	1.000	-1.6465	2.0117
B-Pretest	A-Pretest	2.17478*	.67765	.011	.3457	4.0039
	A-Posttest	2.52565*	.67765	.002	.6965	4.3548
	B-Posttest	2.70826*	.67765	<.001	.8791	4.5374
B-Posttest	A-Pretest	-.53348	.67765	1.000	-2.3626	1.2957
	A-Posttest	-.18261	.67765	1.000	-2.0117	1.6465
	B-Pretest	-2.70826*	.67765	<.001	-4.5374	-.8791

* The mean difference is significant at the 0.05 level.

Completion time of pre- and post-test was analysed for both experimental groups. As illustrated in Table 5.7 and Table 5.8, participants in both groups completed the post-test faster than they did in pre-test ($M_{A\text{-}Pretest} = 7.56 \pm 2.46$ versus $M_{A\text{-}Posttest} = 7.21 \pm 2.38$; $M_{B\text{-}Pretest} = 9.74 \pm 2.80$ versus $M_{B\text{-}Posttest} = 7.03 \pm 1.43$). There was a statistically significant difference between groups as demonstrated by one-way ANOVA [$F(3,88) = 6.85$, $p = <.001$]. Therefore, multiple comparisons were required for determining which specific means differ significantly from others. Post hoc comparisons using Bonferroni correction, as illustrated in Table 5.9, revealed that only group B's participants could reduce their completion time for post-test which is considered statistically significant (p = <.001).

Nevertheless, we cannot conclude that the learning activity with augmented reality had a greater effect on the participants' ability to achieve shorter time of completing the post-test module than those who learned with computer-based multimedia. This is because there was no significant difference in the means of completion time of post-test between group A and group B (mean difference = .18, p = 1.00). A line plot in Figure 5.2 shows the means of completion time varying among different groups.

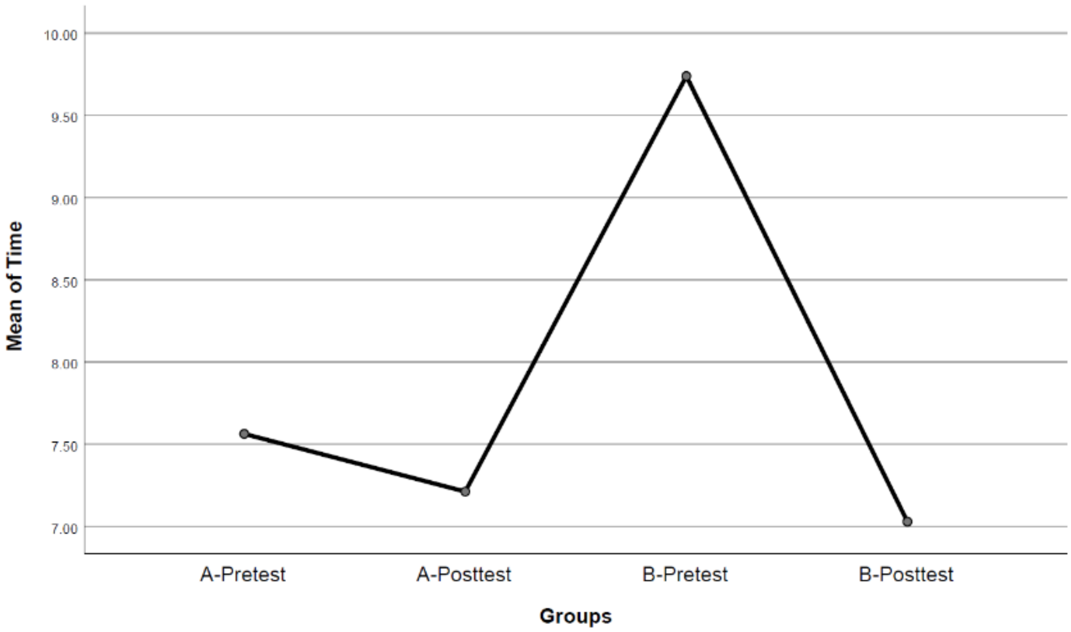
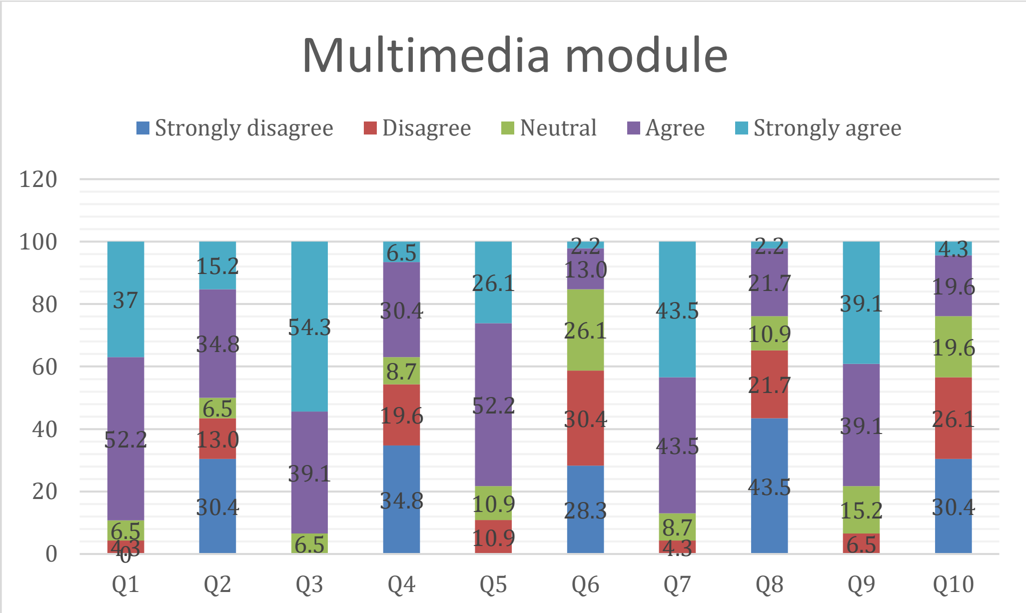


Figure 5.2: Mean of task completion time in both groups of participants

5.4 Analysis of user experience using psychometric instruments

5.4.1 Results from the SUS questionnaire

The first subjective measure that the study looked at is learnability. Learnability can be considered as how easy it is for students to accomplish a learning task at the first time, especially when they encounter the interface of educational media (Sibarani, 2021). Learnability of the proposed learning tools provided in the experiment was evaluated by the SUS questionnaire. All 46 residents were asked to complete the SUS questionnaire form (paper-based) after the second task of self-paced learning activity. All questionnaire data analyses were executed using SPSS statistical software version 28.0. For the items of the SUS, the score was calculated using Brooke's standard scoring method. The SUS score of computer-based multimedia method is 71.63, whereas the SUS score of AR application is 66.68. SUS questionnaire responses for both learning technologies are presented in Figure 5.3 (computer-based multimedia) and Figure 5.4 (AR application). Interestingly, the analyses demonstrated that only the computer-based multimedia received the usability rating which meet the criteria of the standard average of SUS score (≥ 68), as illustrated in Figure 5.5. Therefore, this data could support the assumption that the residents' preference was higher for the multimedia module compared to the AR application.



<u>Note</u>

Q1: I think that I would like to use this computer-based multimedia frequently.

Q2: I found this computer-based multimedia unnecessarily complex.

Q3: I thought this computer-based multimedia was easy to use.

Q4: I think that I would the support of a technical person to be able to use this computer-based multimedia.

Q5: I found the various functions in this computer-based multimedia were well integrated.

Q6: I thought there was too much inconsistency in this computer-based multimedia.

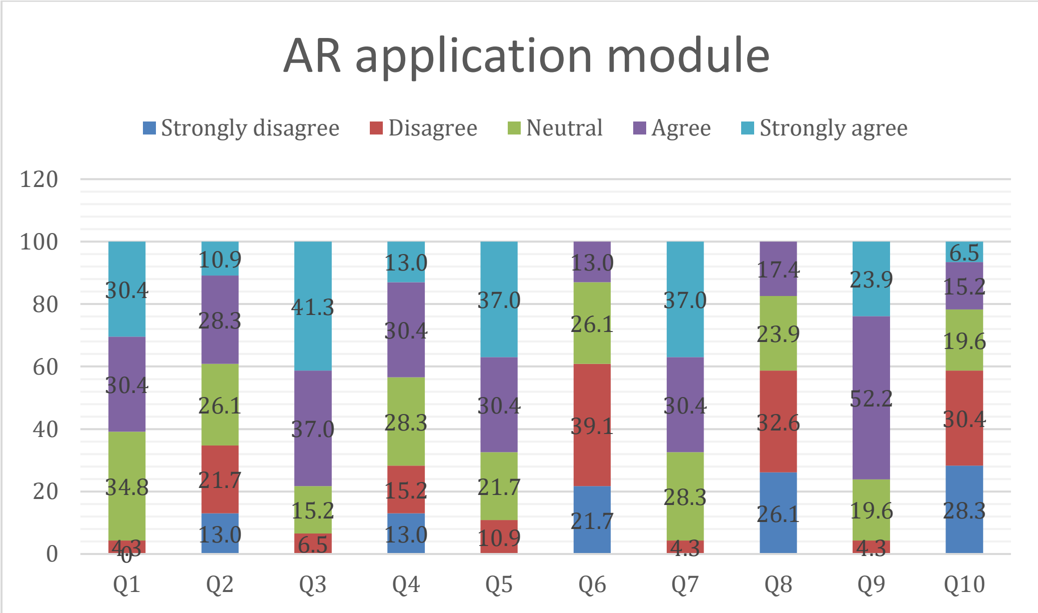
Q7: I would imagine that most people would learn to use this computer-based multimedia very quickly.

Q8: I found this computer-based multimedia very cumbersome to use.

Q9: I felt very confident using this computer-based multimedia.

Q10: I needed to learn a lot of things before I could get going with this computer-based multimedia.

Figure 5.3: Stack chart of percentage for Likert-scale SUS questionnaire feedback for computer-based multimedia



<u>Note</u>

Q1: I think that I would like to use this AR application frequently.

Q2: I found this AR application unnecessarily complex.

Q3: I thought this AR application was easy to use.

Q4: I think that I would the support of a technical person to be able to use this AR application.

Q5: I found the various functions in this AR application were well integrated.

Q6: I thought there was too much inconsistency in this AR application.

Q7: I would imagine that most people would learn to use this AR application very quickly.

Q8: I found this AR application very cumbersome to use.

Q9: I felt very confident using this AR application.

Q10: I needed to learn a lot of things before I could get going with this AR application.

Figure 5.4: Stack chart of percentage for Likert-scale SUS questionnaire feedback for AR application

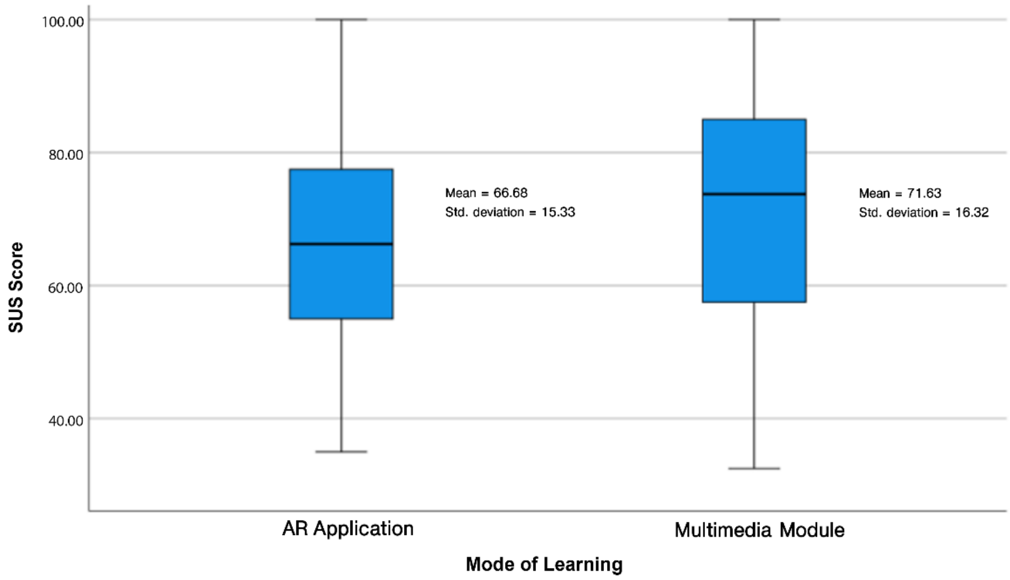


Figure 5.5: SUS scores for AR application and computer-based multimedia conditions

Paired sample t-test was performed to determine whether there is statistical evidence between the SUS scores for AR application versus computer-based multimedia—taken from the 46 participants. As a result, participants' perspectives reflected that AR and computer-based multimedia could serve them at the similar usability goal (the goal with effectiveness, efficiency, and satisfaction) as no statistically significant difference between the SUS scores of the two learning methods was found, $t(45) = 2.10$, $p = 0.41$.

The computer-based multimedia was more preferred by respondents, although no statistical difference was found compared to the AR application. The author was interested in investigating in more details for finding the link between the mean scores of the specific aspects in 10 questions and in total SUS questionnaire. Hence, the mean scores of each question were calculated separately as illustrated in Table 5.10. Comparative analysis of the differences between the pairs of mean scores measured on the same question in the SUS for two different learning modes—the multimedia module versus the AR application was done with a paired sample t-test, with significance set at the 0.05 level.

According to Table 5.10, there are three question statements (item 2, 4 and 8) of the SUS questionnaire which the AR application module received the participants' rating of feedback higher than the computer-based multimedia module. These questions are:

- Question 2: I found this AR application unnecessarily complex.
- Question 4: I think that I would like the support of a technical person to be able to use this AR application.
- Question 8: I found this AR application very cumbersome to use.

The above questions highlighted the residents' feedback on how difficult the AR application was for them to use it in self-paced learning task. However, results of paired sample t-test, as illustrated in Table 5.11, showed that only the difference in mean scores within the Question 4 was statistically significant difference, $t(45) = -3.078$, $p = 0.004$. It could be summarised that the AR application was more complicated to use than the multimedia module and may affect on users' preference. Also, the users' perceptions of usability for AR application were generally correlated with their overall feedback in the SUS questionnaire as shown in Figure 5.5.

Table 5.10: Descriptive statistics on each question (Q1-Q10) of the SUS questionnaire

Item	N	Mean	Std. Deviation	Std. Error
$Q1_{CM}$	46	4.22	.758	.112
$Q1_{AR}$	46	3.87	.909	.134
$Q2_{CM}$	46	2.91	1.532	.226
$Q2_{AR}$	46	3.02	1.220	.180
$Q3_{CM}$	46	4.48	.623	.092
$Q3_{AR}$	46	4.13	.909	.134
$Q4_{CM}$	46	2.54	1.410	.208
$Q4_{AR}$	46	3.15	1.229	.181
$Q5_{CM}$	46	3.93	.904	.133
$Q5_{AR}$	46	3.93	1.020	.150
$Q6_{CM}$	46	2.30	1.093	.161
$Q6_{AR}$	46	2.30	.963	.142
$Q7_{CM}$	46	4.26	.801	.118
$Q7_{AR}$	46	4.00	.919	.135
$Q8_{CM}$	46	2.17	1.270	.187
$Q8_{AR}$	46	2.33	1.055	.156
$Q9_{CM}$	46	4.11	.900	.133
$Q9_{AR}$	46	3.96	.788	.116
$Q10_{CM}$	46	2.41	1.240	.183
$Q10_{AR}$	46	2.41	1.240	.183

Note Q = Question, CM = Computer-based multimedia, AR = Augmented Reality

Table 5.11: Results of paired sample t-test of the means of 10 questions of SUS questionnaire comparing between computer-based multimedia and AR application

Pair	Pair of Variables (Q_{CM} - Q_{AR})	Paired Differences					t	Sig.
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference			
					Lower	Upper		
1	$Q1_{CM}$ - $Q1_{AR}$	.348	1.197	.176	-.008	.703	1.971	.055
2	$Q2_{CM}$ – $Q2_{AR}$	-.109	1.233	.182	-.475	.258	-.598	.553
3	$Q3_{CM}$ – $Q3_{AR}$	.348	1.059	.156	.033	.662	2.228	.031
4	$Q4_{CM}$ – $Q4_{AR}$	-.609	1.341	.198	-1.007	-.210	-3.078	.004
5	$Q5_{CM}$ – $Q5_{AR}$	.000	1.445	.213	-.429	.429	.000	1.000
6	$Q6_{CM}$ – $Q6_{AR}$	.000	.989	.146	-.294	.294	.000	1.000
7	$Q7_{CM}$ – $Q7_{AR}$	.261	1.273	.188	-.117	.639	1.390	.171
8	$Q8_{CM}$ – $Q8_{AR}$	-.152	1.247	.184	-.522	.218	-.828	.412
9	$Q9_{CM}$ – $Q9_{AR}$	.152	1.135	.167	-.185	.489	.910	.368
10	$Q10_{CM}$ - $Q10_{AR}$	.000	1.211	.179	-.360	.360	.000	1.000

Note Q = Question, CM = Computer-based multimedia, AR = Augmented Reality

5.4.2 Results from the SUPR-Q questionnaire

Whereas the above section regarding the results and analyses of SUS questionnaire reflected residents' feedbacks regarding the ease of use of the AR application and the computer-based multimedia proposed in the study, the Standardized User Experience Percentile Rank Questionnaire (SUPR-Q) was used for investigating more specific aspects, which are not assessed through the SUS, including appearance, trust, and loyalty.

46 residents filled out the paper-based SUPR-Q questionnaire immediately after completing the SUS form. For data analysis, SPSS statistical software version 28.0 was used. The method of analysis was based on calculating the mean scores and representing the results of the total SUPR-Q questionnaire and each sub-measurement: usability (ease of use), credibility (trust), appearance and loyalty. The SUPR-Q score of computer-based multimedia method is 4.16, whereas the SUPR-Q score of AR application is 4.18, as illustrated in Figure 5.6. The paired t-test was used to test the mean difference between these mentioned scores and reported as no statistically significant difference found, $t(45) = -0.174$, $p = 0.862$.

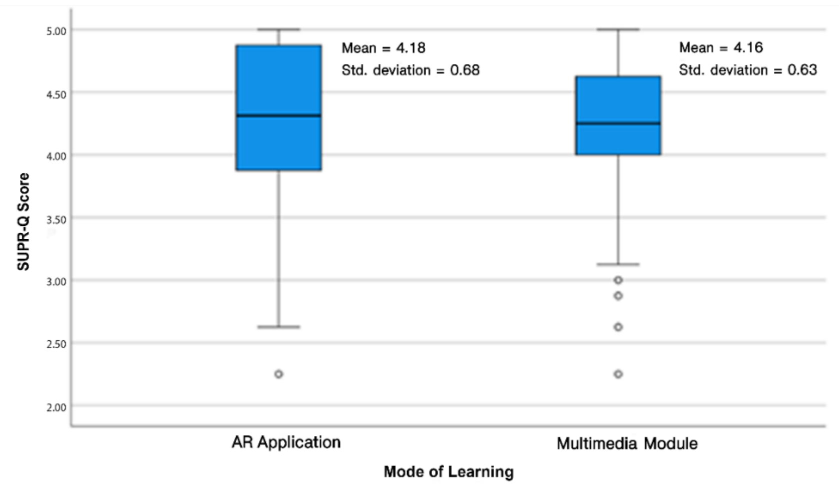


Figure 5.6: SUPR-Q scores for AR application and computer-based multimedia conditions

Additional investigation was analysed based on sub-categories of the SUPR-Q questionnaire. In the analysis, 8 questions were grouped based on four attitude variables: usability, credibility, loyalty, and appearance, each subgroup containing two questions as shown in Table 5.12. Overall, descriptive statistics results indicated that participants considered the computer-based multimedia module was easier to use and they would prefer to recommend it to others and continue using it than the AR application. Moreover, quantitative measure of credibility reflected the perception by participants that the computer-based multimedia and the AR application were similarly credible. Interestingly, results analysis also revealed that participants considered the media features, including text, graphic and 3D visual presentation, of the AR application was more attractive than the multimedia module. However, the results from the paired t-test, with the significance criterion set at p=0.05, showed that there were no statistical differences between the means score of two learning conditions in all sub-measurements, as illustrated in Table 5.13. Therefore, the null hypothesis of the secondary aim that the participants' feedback, relating to subjective measures in the point of usability attributes and subjective satisfaction, towards the AR application are similar to the computer-based multimedia module is accepted.

Table 5.12: Descriptive statistics on sub-measurement of the SUPR-Q questionnaire

Sub-measurement	N	Raw score			
		CM module		AR application	
		Mean	Std. Deviation	Mean	Std. Deviation
Usability (U)					
1. The (CM/AR) is easy to use.	46	4.28	.70	4.24	.76
2. It is easy to navigate within the (CM/AR).	46				
Credibility (C)					
3. The information on this (CM/AR) is credible.	46	4.22	.61	4.22	.73
4. The information on this (CM/AR) is trustworthy.	46				
Loyalty (L)					
5. How likely are you to recommend the (CM/AR) to a friend or colleague?	46	4.12	.86	4.03	.87
6. I will likely return to the (CM/AR) in the future.	46				
Appearance (A)					
7. I find the (CM/AR) to be attractive.	46	4.01	.81	4.23	.72
8. The (CM/AR) has a clean and simple presentation.	46				

Note: CM= Computer-based multimedia, AR = Augmented Reality

Table 5.13: Results of paired sample t-test of the means of each sub-measurement of SUPR-Q questionnaire comparing between computer-based multimedia and AR application

Pair	Pair of Variables (Q_{CM} - Q_{AR})	Paired Differences						
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	Sig.
					Lower	Upper		
1	U_{CM} - U_{AR}	.043	0.965	.142	-.243	.330	.306	.761
2	C_{CM} – C_{AR}	.000	.691	.102	-.205	.205	.000	1.000
3	L_{CM} – L_{AR}	.087	1.235	.182	-.280	.454	.477	.635
4	A_{CM} – A_{AR}	-.217	1.052	.155	-.530	.095	-1.401	.168

Note: CM= Computer-based multimedia, AR = Augmented Reality

5.4.3 Results from the TAM questionnaire

Technology Acceptance Model (TAM) has been widely applied to explain students' acceptance of learning technology in the context of medical education (e.g., Chow et al., 2012; Briz-Ponce and García-Peñalvo, 2015; Zhu and Zhang, 2022). Based on the TAM model, the perceived ease of use (PEOU) is considered as "the degree to which a person believes that using a particular system would be free of effort" (Davis, 1989, p. 320), whereas perceived usefulness (PU) refers to "the degree to which a person believes that using a particular system would enhance his or her job performance" (Davis, 1989, p. 320). It has been examined that PEOU directly impact on perceived usefulness (PU) in TAM model. As illustrated in Figure 5.7, TAM asserts that PEOU and PU influences the users' attitudes to using a new technology system. Behavioural intention to use (BI) can be influenced by users' attitude and perceived usefulness. In sum, BI positively influences users' willingness to accept and use the new technology in real life.

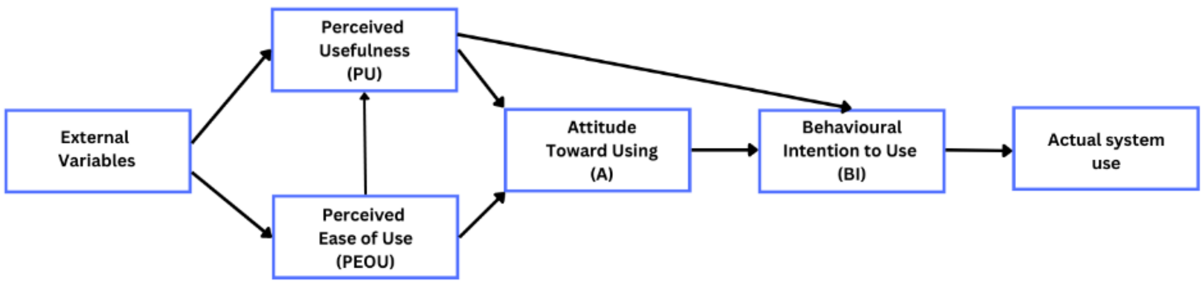


Figure 5.7: Technology Acceptance Model (TAM), partially adapted from Davis et al. (1989, p. 985)

The author hypothesised that the constructs and associations which are described in the TAM model are valid to measure the medical residents' behavioural intention to use the proposed learning media (AR application and computer-based multimedia module) in their real life. With respect to this context, this study tests the following hypotheses:

H1: Perceived ease of use (PEOU) will have a positive effect on perceived usefulness (PU) of the proposed learning media.

H2: Perceived ease of use (PEOU) will have a positive effect on residents' attitude (A) towards the proposed learning media.

H3: Perceived usefulness (PU) will have a positive effect on residents' attitude (A) towards the proposed learning media.

H4: Perceived usefulness (PU) will have a positive effect on residents' intention to use (BI) the proposed learning media.

H5: Residents' attitude (A) will have a positive effect on their intention to use (BI) the proposed learning media.

A structured questionnaire was adapted by reviewing related literature (Masrom, 2007; Tahini, Hone and Liu, 2013). Fourteen factor items were assigned to match four TAM constructs including PEOU, PU, A and BI. PEOU, PU, A and BI were measured on a 5-point Likert-scale, 1 being "Strongly Disagree" and 5 being "Strongly Agree". All 46 residents were asked to complete the TAM questionnaire form after the second task of self-paced learning activity. Data from respondents were imported into SPSS statistical software version 28.0 for descriptive data analysis. The structured questionnaire and descriptive statistics are summarised in Table 5.14.

Table 5.14: Descriptive statistics on sub-measurement of the TAM questionnaire

Constructs	Factor Items	N	Raw score			
			Computer-based multimedia		AR application	
			Mean	Std. Deviation	Mean	Std. Deviation
PEOU	Learning to use (AR/CM) would be easy for me	46	4.61	.577	4.30	.756
	My interaction with (AR/CM) was clear and understandable	46	4.39	.649	4.24	.736
	It would be easy for me to achieve knowledge of basic TTE at the (AR/CM)	46	4.35	.674	4.17	.769
PU	Using (AR/CM) would increase my learning effectiveness	46	4.13	.582	3.89	.674
	Using (AR/CM) would increase my productivity in transthoracic echocardiography training	46	3.87	.619	3.85	.729
	Using (AR/CM) would improve my performance of transthoracic echocardiography exam	46	3.76	.705	3.61	.745
	I found the (AR/CM) useful	46	4.37	.610	4.26	.713
A	I believe it is a good idea to use this (AR/CM) in my residency/echocardiography training	46	4.11	.737	4.07	.827
	I have a generally favourable attitude toward using (AR/CM)	46	4.20	.719	4.15	.842
	I think this (AR/CM) should be a trend of multimedia material in transthoracic echocardiography training	46	4.22	.728	4.15	.842
BI	I intend to use this (AR/CM) during my residency training	46	4.26	.681	4.04	.665
	I would love to use this (AR/CM) during my residency training	46	4.22	.696	4.09	.784
	I hope this (AR/CM) should be provided in my residency training programme	46	4.24	.639	4.04	.788
	I will inform others of the benefit of this (AR/CM) for learning basic transthoracic echocardiography	46	4.24	.705	4.20	.749

Note: PEOU= Perceived Ease of Use, PU= Perceived Usefulness, A= Attitude Toward Using, BI= Behavioural Intention to Use, CM= Computer-based multimedia, AR = Augmented Reality

A reliability analysis was conducted with Cronbach's alpha (α) to investigate the internal consistency reliability of 14 factor items. According to Nunnally (1978), a value of

Cronbach's alpha which is higher than 0.9 is considered as excellent, higher than 0.8 is good, and higher than 0.7 is acceptable. If the Cronbach's alpha value is at 0.60 and below, it can be assumed that the instrument has a low reliability and unacceptable (Nunnally, 1978; Ursashi, Horodnic and Zait, 2015). According to the results in Table 5.15 below, each of four constructs produced values exceeding 0.8, indicating a strong internal consistency reliability of the TAM instrument.

Table 5.15: Cronbach's alpha of PEOU, PU, A and BI constructs

Constructs	Number of Items	Cronbach's Alpha (α)
Perceived Ease of Use (PEOU)	3	0.891
Perceived Usefulness (PU)	4	0.842
Attitude Towards Using (A)	3	0.926
Behavioural Intention to Use (BI)	4	0.920

The statistical technique of Pearson's correlation was performed to verify the strength and direction of the relationship between two variables following each of the five hypotheses related to TAM constructs. In general, a Pearson's correlation coefficient (r) value between 0.60 and 0.79 is considered strong (Wuensch & Evans, 1996). The analysis performed for each type of learning media as shown in Table 5.16 (computer-based multimedia: CM) and Table 5.17 (augmented reality application: AR). As shown in Table 5.16 and Table 5.17, there was a strong correlation between perceived ease of use (PEOU) and perceived usefulness (PU) ($r = .690$, $p <. 01$ for CM; $r = .737$, $p < .01$ for AR). This confirms that the first hypothesis failed to be rejected. The strength of association between PEOU and PU for AR application learning was noticeably higher than the computer-based multimedia. Additionally, PEOU construct was formulated in the second hypothesis to check whether it has a strong relationship with learners' attitude (A) towards using each learning media. The second hypothesis was accepted as there was a strong correlation between PEOU and A ($r = .753$, $p < .01$ for CM; $r = .730$, $p < .01$ for AR). As can be seen, the r value between PEOU and A towards computer-based multimedia was not much different with the r value in AR application case.

Regarding the third hypothesis, there was a strong correlation between perceived usefulness (PU) and learners' attitude (A) towards using each learning medium ($r = .620$, $p < .01$ for CM; $r = .739$, $p < .01$ for AR). Thus, the third hypothesis failed to be rejected as well. For the fourth hypothesis, the strength of correlation between perceived usefulness (PU) and learners' behavioural intention (BI) to use AR application was statistically higher than that of computer-based multimedia learning. As can be seen, the relationship between PU and BI in AR learning was considered strong as the r value was larger than 0.7, whereas the r value in CM learning was considered moderate ($r = .571$, $p < .01$ for CM; $r = .779$, $p < .01$ for AR). Lastly, the fifth hypothesis focuses on the positive influence between learners' attitude (A) and learners' intention to use learning media (BI). There was a strong relationship between A and BI for both learning media ($r = .876$, $p < .01$ for CM; $r = .848$, $p < .01$ for AR). The r value between A and BI to use computer-based multimedia was not much different from the r value in AR application case. This also confirms that the fifth hypothesis failed to be rejected.

Table 5.16: Pearson's correlation matrix for PEOU, PU, A and BI constructs for computer-based multimedia learning

		PEOU Group	PU Group	A Group	BI Group
PEOU Group	Pearson Correlation	1	.690**	.753**	.743**
	Sig. (2-tailed)		<.001	<.001	<.001
	N	46	46	46	46
PU Group	Pearson Correlation	.690**	1	.620**	.571**
	Sig. (2-tailed)	<.001		<.001	<.001
	N	46	46	46	46
A Group	Pearson Correlation	.753**	.620**	1	.876**
	Sig. (2-tailed)	<.001	<.001		<.001
	N	46	46	46	46
BI Group	Pearson Correlation	.743**	.571**	.876**	1
	Sig. (2-tailed)	<.001	<.001	<.001	
	N	46	46	46	46

Table 5.17: Pearson's correlation matrix for PEOU, PU, A and BI constructs for augmented reality application learning

		PEOU Group	PU Group	A Group	BI Group
PEOU Group	Pearson Correlation	1	.737**	.730**	.787**
	Sig. (2-tailed)		<.001	<.001	<.001
	N	46	46	46	46
PU Group	Pearson Correlation	.737**	1	.739**	.779**
	Sig. (2-tailed)	<.001		<.001	<.001
	N	46	46	46	46
A Group	Pearson Correlation	.730**	.739**	1	.848**
	Sig. (2-tailed)	<.001	<.001		<.001
	N	46	46	46	46
BI Group	Pearson Correlation	.787**	.779**	.848**	1
	Sig. (2-tailed)	<.001	<.001	<.001	
	N	46	46	46	46

Path analysis with manifest variables was used to test all the hypothesized relationships among the constructs regarding the research model based on the TAM (see Figure 5.8). In general, the full method of Structural Equation Modelling (SEM) is used for analysing variables in the context of TAM model (Chow et al., 2012; Lee, Hsieh and Chen, 2013; He, Chen and Kitkuakul, 2018; Sholikah and Sutirman, 2020) However, this study employed path analysis method instead of the full SEM approach for analysing data due to the limitation of sample size (N=46). It is recommended that the sample size for conducting SEM method needs to be large. According to the previous experiments and studies, the minimum sample size should be at least 200. This assumption is valid based on various studies documented in literature (Westland, 2010; Wolf et al., 2013; Fan et al., 2016).

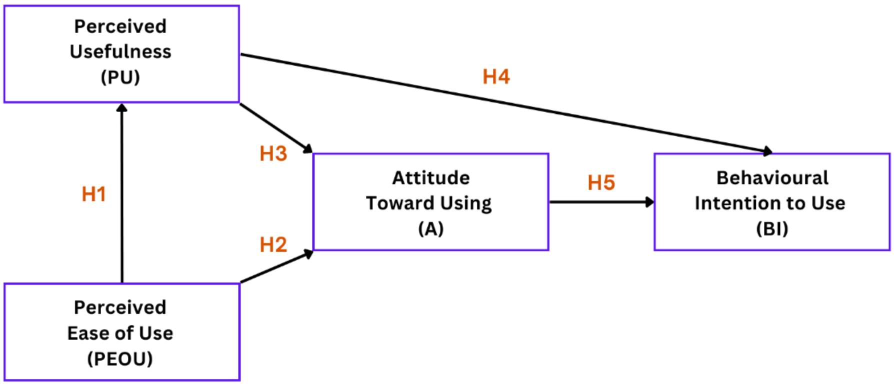


Figure 5.8: The research model

The relationship between variables was analysed through the path analysis approach with AMOS software version 29.0. The model fit results in AMOS comprised of the following indexes/parameters: Chi-square (χ^2) = .206, Degrees of freedom (*df*) = 1. Probability level (*p*) = .206, Goodness of Fit Index (GFI) = .991, Adjust Goodness of Fit Index (AGFI) = .914, Normal Fit Index (NFI) = .994, Comparative Fit Index (CFI) = .998, and Root Mean Square Error of Approximation (RMSEA) = .081.

The findings of the path analysis for the research model were separately represented in Figure 5.9: learners' acceptance of computer-based multimedia and Figure 5.10: learners' acceptance of AR application. Regarding the computer multimedia acceptance, perceived ease of use has a highly statistically significant influence on perceived usefulness (β = 0.82, p < 0.001). Perceived ease of use has a highly statistically significant influence on learners' attitude (β = 0.91, p < 0.001). Attitude toward using has a highly statistically significant influence on learners' behavioural intention to use (β = 0.83, p < 0.001). Perceived usefulness has a statistically significant influence on users' behavioural intention to use (β = 0.28, p < 0.01), but the effect of perceived usefulness on users' attitude was not significant (β = 0.07, p = 0.662).

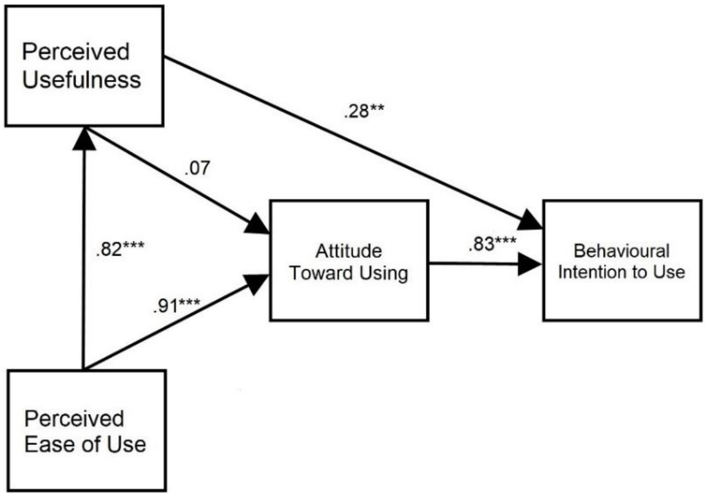


Figure 5.9: Path analysis model and output from learning through computer-based multimedia. Direct standardised regression coefficients (analogous to correlation coefficients) between variables are shown on each arrow; significant values are indicated: *p < 0.05, ** p < 0.01, *** p < 0.001.

Regarding the AR application acceptance, interestingly, all paths of relationships between TAM variables regarding all five hypotheses were statistically significant. Perceived ease of use has a highly statistically significant influence on perceived usefulness (β = 0.86, p < 0.001). Perceived ease of use has a highly statistically significant on learners' attitude (β = 0.62, p < 0.001). Perceived usefulness has a statistically significant influence on users' attitude (β = 0.36, p < 0.005). Perceived usefulness has a statistically significant influence on users' behavioural intention to use (β = 0.39, p < 0.005). Attitude toward using has a highly statistically significant on learners' behavioural intention to use (β = 0.54, p < 0.001).

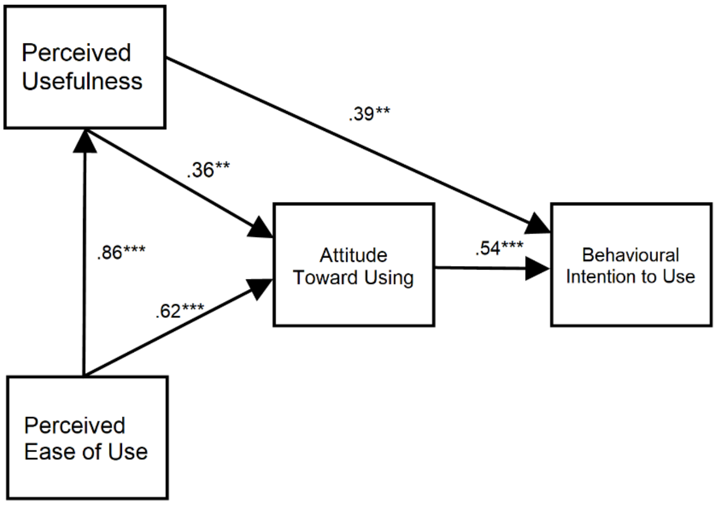


Figure 5.10: Path analysis model and output from learning through augmented reality (AR) app.
Direct standardised regression coefficients (analogous to correlation coefficients) between variables are shown on each arrow; significant values are indicated: *p < 0.05, ** p < 0.01, *** p < 0.001.

5.5 Anecdotal Feedback

Besides the SUS and SUPR-Q questionnaires used for subjective measurements, the evaluation survey included an open-ended question for respondents to share comments or suggestion about their experiences with proposed learning technologies used in the experiment. Among 46 participants, only eleven (24%) participants shared their personal comments about the experiment. All written responses to this open-ended question are summarised and listed in Table 5.18.

Table 5.18: Participant Additional Comments or Suggestions about The Experiment

Comment/Suggestion	Details	Count (Total =11)	Percent
Expecting to use a greater version of mannequin-based simulator which provides a better simulated experience with higher technology than the marker-based AR application in the future	- Providing a mock transducer probe for practicing the actual transthoracic echocardiography exam on a life-size mannequin	9	81%
	- Providing other optional accessories, e.g., a head-mounted display (HMD) for visualising 3D animated presentation overlaid onto the mannequin	5	45%
	- Providing the 360 view of 3D animated objects which can be directly seen over top of the mannequin	9	81%
Improving both the computer-based multimedia and the AR application modules to have other related educational content	- Transoesophageal echocardiography (TOE)	1	9%
	Common investigations in cardiovascular disease such as - Ejection fraction heart failure measurement (EF) - Regional wall motion abnormalities (RWMA) - Stenosis - Regurgitation	6	54%

5.6 Conclusion

In this thesis, the exploratory case study was set to test three research aims. The first aim was to determine whether the use of 3D visualisation delivered through two different technologies (computer-based multimedia and AR application) really help improve understanding of basic TTE. The results from the objective measurement (the pre- and post-test design) proved the positive effect of the proposed learning medias in enhancing knowledge construction of the residents about basic transthoracic echocardiography as there were significant difference between pre- and post-test scores in both two intervention groups—the AR application and the computer-based multimedia groups. The comparison of the pre-test scores was executed to assure that there was no bias in the participants' knowledge background between both cohorts in the study. Therefore, the null hypothesis is that participants cannot show significantly greater gains in scores between pre-and post-test scores is rejected.

The second aim was set within the scope of the hypothesis that the AR application could have more potential impact than the computer-based multimedia in supporting residents' knowledge and understanding of anatomical structures regarding four basic transthoracic echocardiographic views. This aim was investigated based on two dependent variables including gain scores between the pre-and post-test, and task completion time. As a result, no statistically significant difference of the means of the post-test scores between two intervention groups was reported. Another aspect related to the analysis of the task completion time reported that only the participants in the AR application group consumed significantly less time for completing the post-test than the pre-test. However, this finding could not be presumed that this is the impact of the AR technology-assisted learning towards the learners as there was no significant difference of the means of completion time of post-test between two groups. Hence, the null hypothesis is that there are no statistically significant differences in learners' knowledge improvement between two groups of learning media is accepted—AR application has no greater impact on the residents' knowledge and understanding improvement about basic TTE than computer-based multimedia.

The final aim is addressed for investigating insight into the subjective aspects of learning experience. Information regarding usability was collected using rating-scale questionnaires—the System Usability Scale (SUS), the Standardized User Experience Percentile Rank Questionnaire (SUPR-Q), and the Technology Acceptance Model (TAM)—and the open-ended question allowing the respondents to share their new ideas or provide comments based on their understanding and experience in learning with the AR application and the computer-based multimedia. The results from the SUS—measuring usability, and the SUPR-Q—measuring ease of use, trust, loyalty (willingness to use the proposed learning medias in the future), and appearance—reported that the residents preferred to use the computer-based multimedia than the AR application but no statistically significant difference between them was found. By focusing on details of the respondents' feedback, the AR application's interface was more complicated and confusing to use yet its presentation was more interesting and attractive than the computer-based multimedia. Additionally, both proposed medias were received similar ratings of creditability as educational resources for learning basic TTE.

The TAM model is used as the baseline model to identify residents' acceptance of the proposed learning medias. Five sub-hypotheses were set to analyse the correlation among TAM variables including the perceived ease of use (PEOU), perceived usefulness (PU), attitude toward using (A) and behavioural intention to use (BI). The results of the path analysis for the research model indicated that there were some differences of users' acceptance between computer-based multimedia (CM) and AR application. Regarding the acceptance of computer-based multimedia, there were statistically significant relationships in four hypotheses including H1 (PEOU and PU), H2 (PEOU and A), H4 (PU and BI) and H5 (A and BI). However, the results do not establish support for hypothesis H3, where the path between perceived usefulness (PU) and attitude toward using (A) was not statistically significant. Interestingly, all paths of relationships between TAM variables in learners' acceptance of AR application showed very highly statistically significant relationships (p < 0.001). Overall, the null hypothesis is accepted, and it can be concluded that the participants' feedbacks in regarding usability attributes, subjective satisfaction, and acceptance towards both learning medias are not significantly different.

Anecdotal evidence obtained from the open-ended question suggests a range of views. To sum up, these suggestions were aligned with the demand of an improved version of the AR application. As the respondents expected to improve their image acquisition skill by practising with a mock transducer probe on the torso mannequin while still seeing 3D animated visualisation augmented onto the physical environment. This idea grounds to the idea of the future work which will hopefully lead to the implementation of the mixed reality (MR) system integrated with the technology of real-time tracking system embedded on the dummy probe which better mimic the actual echocardiography examination with the torso mannequin. Moreover, the respondents also shared impressions towards the 3D animated visualisation represented in both the AR application and the computer-based multimedia which positively supported their learning. Therefore, they expected these learning medias should include more educational contents to broaden the understanding in echocardiography, for example, common cardiac pathologies shown in an echo image including ejection fraction heart failure assessment, regional wall motion abnormalities (RWMA), stenosis, and regurgitation.

Chapter 6

Conclusions

6.1 Results interpretation

The PhD project outlined in this thesis set out to develop and evaluate the effectiveness of learning technologies being suitable for providing flexible, self-directed, learning opportunities for novice trainees to learn the fundamental of transthoracic echocardiography (TTE). Before the procedure of developing learning materials and design of the exploratory case study, a series of research questions were developed based on anecdotal evidence from internet searches and meetings with clinical subject matter experts associated with the study. These questions (Q) are as follow:

Q1: What are the current educational technology trends that are supporting TTE education?

Q2: How familiar are medical trainees with augmented reality technologies and applications?

Q3: How does visual representation fidelity in technology-mediated learning tools affect learners' understanding about the complex spatial relationships between the TTE image and the cardiac anatomy?

Q4: How does visual representation fidelity in technology-mediated learning tools affect user acceptance and usability?

In the initial stage, the first research question was set to investigate the recent trend of learning technologies used for supporting echocardiography education. By conducting the literature review, it helped to identify the research gaps that led to research objectives and were used as reference points to design the exploratory case study.

Many interesting and important findings about current echocardiography education have appeared. By concentrating on echocardiography training, the idea of adopting technology as educational tools is generally based on solving the problems existing in current training pathways including limited training time for trainees, and a serious deficit of trained echocardiography professionals. A review of a range of studies found a growing demand for digital learning solutions with the purposes of reinforcing the knowledge learnt both in and out of the classroom or as an integral part of hands-on echocardiography practice. The prevalent echocardiography training curricula are designed with flexibility and objectivity that allow self-directed and self-paced learning. This involvement is frequently supported using web-based multimedia instruction (WBMI) and simulation. The common pedagogical design found in the existing literature is a hybrid learning approach which includes lectures, web-based multimedia, and a hands-on session equipped with mannequin-based simulators.

A wide body of research relating to the assessments of learning outcomes that medical trainees achieved in the echocardiography course or module showed that the multimedia instruction module's effectiveness is closely related to the development of students' knowledge and understanding, whereas echocardiography simulators impact on honing procedural skills (such as probe placement on the patient) which can most effectively be learned via hands-on training. To the best of the author's knowledge, no previous studies were conducted to directly evaluate, or compare, the effectiveness (contributions to the learner's knowledge and competencies) of different technologies of learning tools which provided the same echocardiography content.

The scope of the first research question also focused to investigate the trend of learning materials enhanced with 3D visualisation technology used for echocardiography education. Immersive technology—including AR, VR or MR—was in the main interest as it has been a recent technological evolution changing the way of medical training. Whereas simulation-based education and web-based instruction module have entered the prolonged widespread use in medical education, immersive technology is currently in the spotlight of medical education as it can solve some of the existing learning methods' drawbacks that may limit students' learning and interaction. Potential pedagogical benefits of using immersive healthcare training have been addressed. For example, VR can offer the immersed viewpoint of a 3D display that can enhance the levels of immersion and interaction rather than studying or attending online classes. AR supplements the learner's view of the physical world with 3D visual overlays which could be a reference of the invisible anatomical structures assisting them in understanding the complicated medical concepts. However, not many published studies reported the substantial evidence of the effectiveness of immersive tech (primarily focusing on AR) to medical students with respect to knowledge development toward echocardiography education.

Promoting personalised, self-paced and self-directed learning about the basic TTE was the rationale behind the design of the research protocol. Computer-based multimedia and AR technologies were taken into consideration to be the main factors to study how they influence the medical trainees' knowledge gains and satisfaction with interactivity in self-directed learning sessions. Each of the technologies have their own benefits and shortcomings. For example, the use of online multimedia modules remains constant throughout the years in echocardiography training as its flexibility—providing users the opportunity to learn at any place and any time—for grounding trainees before attending hands-on practice sessions with the simulator or the role-play patient. However, most experimental studies prior to this PhD study only compared the effectiveness of online multimedia module as a learning tool with that of lectures. Whereas multimedia instruction module has a long history in most fields of medical education, AR technique (including its cousin technologies: VR or MR) has just gained the spotlight by providing cutting-edge technologies, including the real world enhanced with 3D digital objects, real-time interactive learning experience, and proposing a 3D registration-based perception (the process of accurately matching the virtual objects at the expected location with respect to the real environment). However, such research is still in an early stage, without any clear conclusion or recommendation about the medium and the technique of utilisation of AR application in echo training. Therefore, further studies are required to confirm educational benefits of AR in echocardiography education.

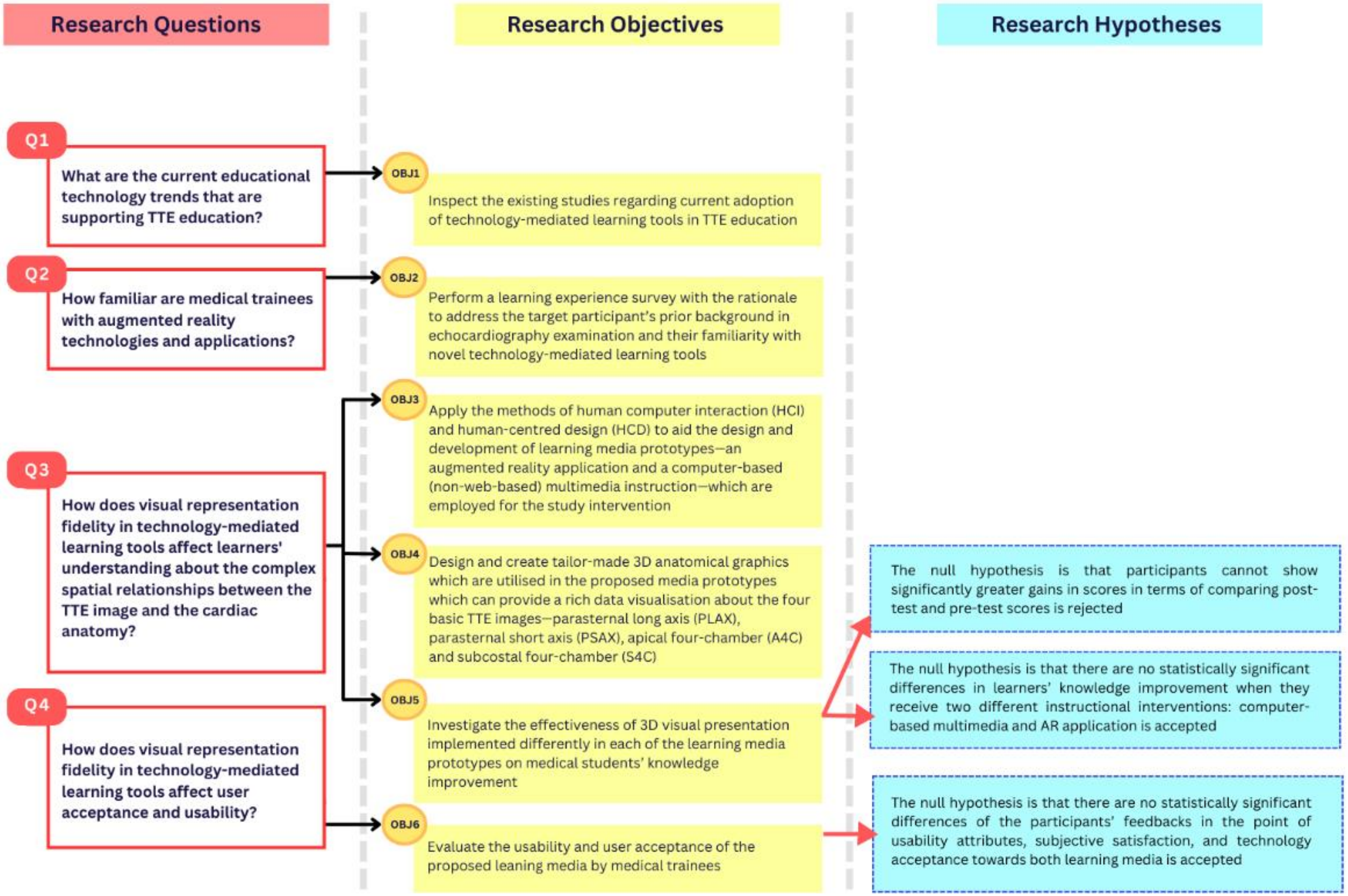


Figure 6.1: Relationship among research questions, research objectives and research hypotheses

The other questions were clearly defined, and objectives were set in advance as shown in Figure 6.1. The second research question was set based on the objective for target population analysis. The questionnaire survey was used for this purpose. It was guided by the concept of learning need assessment (LNA). LNA is generally defined as an important initial groundwork in an educational process to identify the actual situation and the real need of learners for determining how learners will best gain from the new design of training pathways or educational systems (Grant, 2002). With regards to the analysis of target participants, the Thai internal medicine residents—their grade of medical practitioner is similar to the level of foundation doctor in the UK—were well suited to this PhD study as most of them had prior experience of external ultrasound scan to examine the lung, other organs or structures within the abdomen, and the condition of a pregnant woman and her embryo or foetus, but novice to transthoracic echocardiography (TTE). Most participants were likely to learn more about TTE as they reflected on the survey that being competent in TTE is very important to their future career.

Ultimately, the final section of the survey was aimed to investigate the participants' familiarity with AR technology. The result showed that although AR utilisation has been thriving as a recent worldwide trend in medical education—as stated in the Chapter 2: Literature review, it is still not widely used in Thailand as most participants admitted that they knew very little about it. However, the author assumed that this might not cause the participants any trouble using AR application in the exploratory case study as they had an average age of 28 being generally comfortable and familiar with using a smartphone or tablet.

The third question focuses on the influence of visual representation fidelity in technology-mediated learning tools on learners' knowledge improvement. The concept of visual representation stemmed from one of the human cognition-related theories—the cognitive affective model of immersive learning (CAMIL) (Makransky and Petersen, 2021). The CAMIL is evolved based on the cognitive load theory (CLT) which focuses on related factors influencing the design of learning technology for maximising learners' germane load and minimising the amount of intrinsic and extraneous cognitive load. According to the CAMIL, the interactive immersive digital environment can elevate the learners' experience regarding procedural knowledge or psychomotor skills training. However, the instructors should draw intense attention to avoid some unrelated interactive features and unnecessary 3D imagery as these can hinder learning and increase the level of intrinsic motivation and extraneous cognitive load on learners (Makransky and Petersen, 2021).

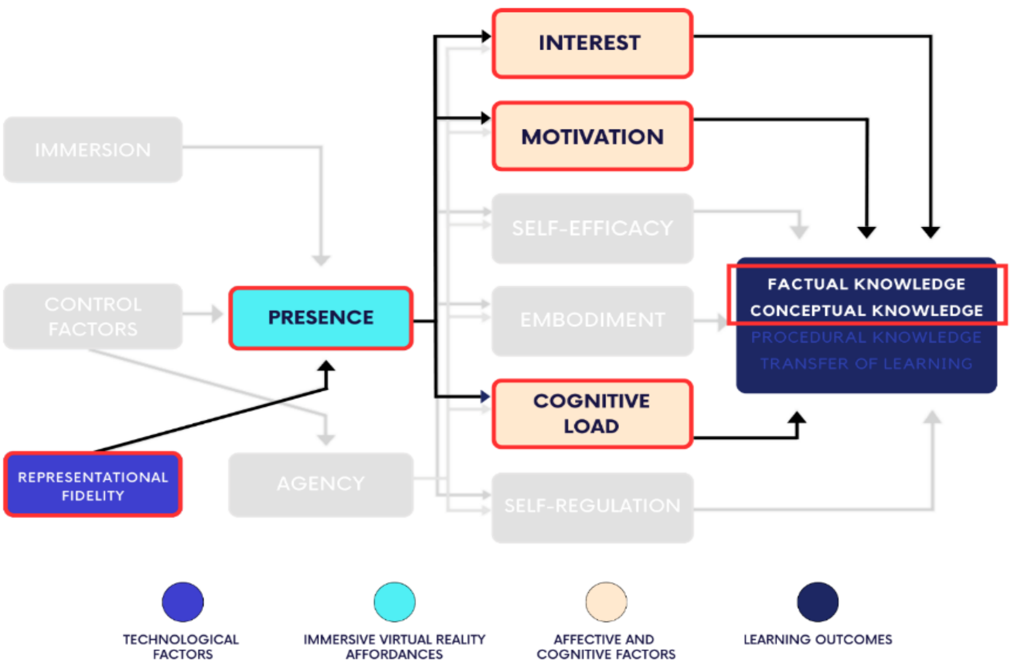


Figure 6.2: The thesis investigation' framework based on the CAMIL

In this thesis study, visual representation fidelity is the core of interest as it is an important technological factor for learners to develop their mental representations leading to knowledge construction and memory processes (Cromley, Snyder-Hogan and Luciw-Dubas, 2010; Moreno 2006). Many factors of learning media are considered having strong influences on learners' visual perception including display technologies, the perception of smoothness while interacting with the display, and the correspondence between the realism of visualisation and users' sensory perception (Dalgano and Lee, 2010).

Therefore, this PhD investigation addressed the development of new proposed learning systems—an augmented reality (AR) application and a computer-based (non-web-based) multimedia instruction—which are designed to deliver different graphic representation fidelity to learners. Factual knowledge—bits of basic knowledge of terminology, and conceptual knowledge—complex structured knowledge, of basic transthoracic echocardiography are defined as the required learning outcomes. Additionally, from the Figure 6.2, the scope of the investigation also covers two important CAMIL's factors—interest and motivation. These two factors are linked with testing benchmark for evaluation of the learning media prototypes regarding usability, subjective satisfaction, and technology acceptance.

Regarding the design process of the proposed learning media, the human computer interaction (HCI) in conjunction with the human-centred design (HCD) were employed. A primary goal of utilising HCI and HCD in this study is to improve the interactions between medical trainees and the computer systems of the proposed learning media. The user interface (UI) and user experience (UX) of the AR application and the computer-based multimedia module were designed to be receptive to the learners' needs and minimise the barriers between the computer interactive systems and the human characteristics of communication.

The third research question was also related to objective assessment of knowledge gained in target residents exposed to two different educational media—computer-based multimedia (CM) module and AR application. A comprehensive prediction was that the AR application was more effective than the computer-based multimedia in enhancing residents' basic TTE knowledge. The justification behind this prediction is that although the proposed two learning formats presented identical contents and graphics, the AR application offered a higher visual graphic representation fidelity than the CM module. The marker-based AR application enabled residents to view 3D animated objects—regarding anatomical knowledge, ultrasound probe positioning, and recognition of anatomical structures identified on four standard TTE windows—overlaid onto the male torso mannequin placed in the supine position.

In terms of the field of study related to an impact of learning media on knowledge development and retention, researchers should be concerned about possible bias of participants' educational background—the mediating impact of prior knowledge when implementing the educational interventions, teaching, or learning strategies based on the utilisation of technology-based learning materials (Austin, 2009; HEW and LO, 2018). Regarding this PhD thesis, the pre-test results of knowledge demonstrated that all internal medicine residents shared a similar proficiency in the basic TTE knowledge. It is consequently unlikely that prior knowledge had an impact on participants' knowledge gain after the trial.

However, the author's prediction was rejected as no significant difference on post-test scores between interventional groups (group A: learning with the computer-based multimedia, and group B: learning with the AR application) was found. Therefore, it cannot be guaranteed that the cutting-edge technology of AR application can provide better effect on improving learning outcomes improvements than a more traditional learning method with multimedia module.

The last question was aimed at identifying trainees' feedback on the usability attribute, indication subjective satisfaction, and user acceptance in using the provided learning media. A multi-modal research instrument combining three standardised questionnaires (the SUS, the SUPR-Q, and the TAM model) and the open-ended question focused on the residents' views and perceptions were used. Considering the analyses from the SUS and the SUPR-Q results, no statistically significant difference was found in overall residents' attitude towards four parameters in the questionnaires, including learnability (ease of use), credibility, appearance, and loyalty. When looking in more details, the interface and features on the multimedia module were rated as being easier to use than the AR application. However, graphics and interactive 3D representation of the AR application received higher preference scores than the computer-based multimedia. Regarding the TAM results, the findings informed that the research model—based on four TAM constructs (PEOU, PU, A and BI) has successfully explained residents' acceptance of the proposed learning media. The learners' acceptance toward the use of computer-based multimedia showed that perceived ease of use (PEOU) was the strongest positive factor affecting residents' attitude (A) (β = 0.91, p < 0.001). Meanwhile, perceived ease of use (PEOU) has the strongest influence on perceived usefulness (PU) of AR application (β = 0.86, p < 0.001). In sum, this exploratory case study found that the perceived ease of use is the most influential factor on learner acceptance and satisfaction for using learning media technologies.

6.2 Discussion

Considering the mentioned research results, several observations were made. The pre- and post-test scores confirmed that the knowledge of all participants improved after either learning with the computer-based multimedia or the AR application, but participants between two groups of the case study did not report significantly different levels in knowledge improvement. This is partly in conflict with the author's expectation that residents should obtain more educational benefits from the visual representation fidelity of AR application than from the desktop-based multimedia module. Surprisingly and opposite to the expectation, the AR application received lower preference ratings than the computer-based multimedia regarding the perceived ease of use. Several possible assumptions leading to the results of this study were investigated based on previous studies in reference to learners' visual perception regarding the use of technological media materials as well as strengths and weaknesses of AR learning systems for medical education.

6.2.1 The influences of learning media on student learning outcome and cognitive load

Regarding human information processing and cognition, people can gather information and construct their own knowledge based on two processing systems: visual channel and auditory channel. Information processing starts in sensory memory, constructs the knowledge in working memory, and eventually integrates new knowledge with prior knowledge in long-term memory. The use of visual presentation in learning media can make a complex lesson clearer and easier to understand; however, its excessive use can lead to increased students' cognitive load or reduced satisfaction with learning.

In many studies, the use of innovative visualisation of new media cannot guarantee significantly better learning outcomes compared to traditional learning styles. For example, although high-fidelity 3D visualisation employed in computer simulations can revolutionise aspects of teaching and enrich learning experience, many studies reported that those computer simulations were not more effective than traditional instructional methods in supporting students' knowledge construction in a medical science context (Hariri et al., 2004; Marbach-Ad et al., 2008; Koć-Januchta et al., 2022). When investigating more into details of these studies, there are several possible reasons why the novel learning technologies failed to prove more effective than traditional methods of learning. Most reasons are arise from students' extraneous load and intrinsic load. For example, extraneous cognitive overload can result from visual representation of excessive texts, graphic disturbances and unnecessary animated contents of learning media which negatively impact on students' working memory. Intrinsic cognitive load can be increased when students fail to follow instructions because some novel learning materials or techniques—e.g., high-fidelity simulators, and virtual reality (VR) applications—are found to be too complicated to use and are more time-consuming than reading textbooks or using traditional learning materials (Hariri et al., 2004; Marbach-Ad et al., 2008; Yue et al., 2013; Mayer 2014; McCoy, Lewis and Dalton, 2016). Regarding visual perception, cognitive load can also be associated with visual fatigue or digital eye strain caused by prolonged computer or digital device usage during learning tasks (McCoy, Lewis and Dalton, 2016; Souchet et al., 2021).

The implementation of digital visualisation in many forms of learning media and materials can stimulate students' motivation and learning engagement (Nahari & Alfadda, 2016; Matveeva et al., 2023); however, there were studies conducted and demonstrated that if any high-fidelity interactive visualisation medium was perceived as being too difficult to use, students would still prefer learning with traditional resources—e.g., textbooks and videos (Soman et al., 2010; Smetana & Bell, 2012). According to the results of this thesis, although the interactive visualisation—a partially immersive learning experience—offered by the AR application impressed resident trainees, it received lower preference ratings than the computer-based multimedia regarding the perceived ease of use. This finding can be supported by previous studies which defined the causes of learner dissatisfaction with educational materials including unfamiliar user interface, a lack of introduction (or a user manual) on how media can be used to achieve successful learning, and technical difficulties (Hariri et al., 2004; Kintu et al., 2017). In sum, the positive effects on learner's perceived usability towards a learning medium are increased if that learning medium is designed to be easy to use and to minimise cognitive load.

6.2.2 Strengths and weaknesses of AR-based learning systems

As stated in Chapter 1 (Introduction) and Chapter 2 (Literature Review) regarding the role of AR as a learning technology in science and medical education, AR can promote the novel learning opportunities where virtual learning experiences can be embedded within a physical environment. Many studies show the wide range of AR utilization in healthcare education including making the invisible view inside the human body visible that helps learners to cultivate better understandings of spatial relationships associated with anatomy (Bogomolova, 2020; Bork, 2019; Henssen et al., 2020; Moro, 2017), providing training opportunities to assure competence in the clinical setting (Bretón-López et al., 2010; Mousavi Hondori et al., 2013; Lamounier et al., 2010), and offering alternative ways for acquiring and strengthening complex surgical skills (Logishetty et al., 2019; Rochlen et al., 2017). Focusing on previous studies carried out with regard to the strategy for making the student more active in acquiring medical knowledge and skills, evidence from research showed that AR could benefit in reducing failure rate and improved medical performance accuracy, lessening the amount of time and practice needed, and reducing the teaching load (Zhu, Hadadgar, Masiello and Zary, 2014).

Although the AR learning approach certainly has great educational benefits as mentioned, AR technology implementation in medical education may be challenging if its presentation—the interactive system or the experiences—is not well served for pedagogical purposes. Some previous studies which had results in line with the results of this PhD study—no significant difference in learning outcomes was found between the AR-based and the computer-based multimedia—pointed out that AR could not somehow provide better effectiveness than the traditional learning methods they normally used. For example, there was evidence that students who experienced AR applications showed increased knowledge similar to that of those students who learned with the other more conventional learning materials, such as the 2D anatomical atlas (Bogomolova et al., 2020), the traditional 2D flashcards (Noll, von Jan, Raap and Albrecht, 2017).

Interestingly, there were some previous studies addressing how the traditional ways of teaching methods were better suited for pedagogical approaches than AR. Such outcomes had been described in a study by Henssen et al. (2019) which showed that studying neuroanatomy using cross-sections of specimens was more efficient, more effective and better suited for visualizing anatomical structures than the tablet-based AR application. They found that although the advantage of AR application included helping learners process existing ideas of neuroanatomy concepts with less cognitive load, cross-sections of specimens offered a better way to transfer knowledge that was more practical and associated with the learners' performance in the cross-sectional test or the actual clinical setting in the future. Besides training with learning materials, traditional teaching methods using didactics and expert role modelling are well suited to some medical training tasks rather than AR utilisation such as hip replacement surgery (Logishetty et al., 2019).

Overall, potential factors which may cause the challenges of using augmented reality within medical education should be further investigated. The most pertinent point is that a teacher or an instructional designer should be cautious of how to match learning requirements with the most appropriate design which will guide the development of AR-based educational solutions. In general, AR, including its cousin technologies (VR and MR), are a promising addition to learning experiences due to their ability to share educational concepts in new and engaging ways. With AR, learners can interact with digital overlays of virtual objects that appear within their physical surroundings. However, AR applications are often influenced by theories and methods of visual graphics and game-based learning which may not always be pedagogically effective solutions (Erturk and Reynolds, 2020). This can cause learners to feel scattered and disjointed with AR experience unrelated to skills or practical experience as they are faced in the real clinical settings.

6.3 Future works

The abovementioned literature search was conducted in support of the results of this PhD study. It is also helpful to enlighten the author to highlight the contributions of the present study. The research contribution is to provide the related opportunities for further developing the proposed AR application system in a more suitable approach used for transthoracic echocardiography. Ideas for future development are as follows:

- ***Enhancing relevant technological properties of the learning material: from augmented reality (AR) to mixed reality (MR)***

  The author acknowledges that the proposed AR application used in this study has several limitations stemming from the optimisation method and hardware implementations. As the exploratory case study was conducted during the Coronavirus (COVID-19) pandemic in 2020, any performing tasks with the hands and using a wearable headset attached to the user's face were removed from the trial for minimising COVID-19 transmission risk. The tablet-based AR system had an advantage over the desktop-based learning platform in providing the simulated 3D visualisation and orientation guidance for improving their conceptual understanding of spatial relationship between probe positioning and views for TTE overlaid on the mannequin. With the marker-based AR application, the users interacted with 3D digital elements, which were superimposed into the real-world, on the high-resolution tablet screen using finger gestures whereas they used the operability of laptop's keyboard and a mouse in desktop-based learning environment. Thus, the user interaction with tablet-based AR application offered in the trial did not differ much from the computer-based multimedia.

The proposed design of further development aimed at increasing fidelity of the immersive media-based learning by more closely simulating a realistic scenario of transthoracic echocardiography examination. Anecdotal feedback from the participants, as shown in Section 5.5, indicated that they were impressed with 3D presentation and visualisation of AR application; however, they expected more engagement with better learning tasks including using a mock transducer probe for practicing transducer handling and TTE image acquisition skills in relation to the actual transthoracic echocardiography exam on a mannequin, using an alternative device, e.g., a transparent head-mounted display for visualising 3D digital content instead of holding a tablet, and providing the 360 view of 3D animated objects which can be directly seen over top of the mannequin in real-time. With these abovementioned findings, the future further development of the framework will be changed from AR to MR.

- ***Providing an introductory session about immersive technology for learners***

The findings from this research regarding usability test showed the residents' reflection concerning interactive system of the proposed learning media. Interesting 'negative' feedback arose regarding experiential issues of the actual use of the AR system (see Subsection 5.4.1) which stated around three issues based on Question 2, 4 and 8 of the SUS questionnaires:

i) I found this AR application unnecessarily complex,
ii) I think that I would like the support of a technical person to be able to use this AR application, and
iii) I found this AR application very cumbersome to use.

These above-mentioned aspects are relevant to affordance of AR technology. The essence of the word 'affordance' in the context of human computer interaction (HCI) lies within the concept of an action possibility in relation between the interface and the user. Specifically, a well-planned user interface (UI) design should have the quality to clarify user's perception on how a computer application can be or should be used (Steffen et al., 2019). In general, there is no single general framework available to use in every immersive media-based (VR/AR) learning system. Parson and MacCullum (2021) made a suggestion that presented the key affordances that should be applied in designing AR learning systems in medical education: 1) reducing negative impact (risk, cost), 2) visualising the otherwise invisible, 3) developing practical in a spatial context, 4) device portability across locations, and 5) situated learning in context (Parson and MacCullum, 2021).

Besides focusing on the implementation of specific affordances for further developing MR system being most effective in the domain of learning in TTE, the introductory session about immersive technology should be provided for the potential learners before experiencing with MR learning system. The important of this session is to prepare and motivate students who may have different preferences and levels of experience with learning technologies before using MR application.

Further study could be undertaken to repeat the exploratory case study within this PhD study but with a new MR system instead of the AR application. As mentioned above, the implementation of technical details and techniques of visualisation modality and tracking system integrated in the MR system will be improved. A key aspect in the development of the future design of MR system is to provide the interactive learning tasks that are more closely related to a realistic scenario of TTE examination. Medical trainees could have an extensive learning experience with an AR head-worn display and a hand controller which let them interact with virtual elements and real objects in real-time through high-level imaging and sensing technology. Whereas the headset displays information on a transparent screen in the learner's view, a hand controller is equipped with tracking precision system which detects user's hand and finger movement for simulating probe movement skills. Additionally, as mentioned in Section 5.5, future development of the MR system and the computer-based multimedia module should extend the educational content to include pathological abnormalities that can potentially be diagnosed by echocardiography, e.g., ejection fraction heart failure measurement (EF), regional wall motion abnormalities (RWMA), stenosis, and regurgitation. In sum, the purpose of the MR system is expected to support TTE learning in response to medical trainees' expected learning experience.

6.4 Conclusions

In conclusion, this thesis reports findings on whether the use of interactive 3D visual presentation combined with different types of learning media—computer-based multimedia module and augmented reality (AR) application—contributes to the medical residents' knowledge improvement in basic transthoracic echocardiography (TTE). Immersive technology—AR, virtual reality (VR) and mixed reality (MR) technologies— is still considered an emerging learning technology in the field in echocardiography education, with most studies reporting early prototypes. Thus, this study was undertaken because the author did not find any published study on the theme of the utilisation of immersive tech for TTE education, especially when it is used in a self-directed learning approach.

It should be noted that the case study presented in this thesis was conducted during the outbreak of COVID-19. This caused several limitations of this study. The most significant limitation was sample size of voluntary medical residents, affecting the statistical power of the study results. Moreover, the COVID-19 pandemic affected the author in carrying out this research and making the final decision to reject the development of an MR simulator used for the exploratory case study. Using the MR simulator could be identified as a risk factor increasing COVID-19 disease transmission because the simulator equipment (including a wearable headset and controllers) was meant for communal use for the group of the target participants. The tablet-based AR application was developed for using in the study instead.

The main contribution of this PhD study is the creation of animated 3D models for the specific purpose of representing the four basic transthoracic echocardiographic views. The design and development pipeline of 3D animated models stated in this thesis has never been mentioned in earlier related studies. The theoretical frameworks including human cognition-related theories, human computer interaction (HCI) principles, and human-centred design (HCD) approach were applied as parts of the instructional design to guide the development and implementation of the proposed learning media in TTE education.

The research results provide evidence that no significant difference in contribution to the learners' achievement was found between the computer-based multimedia module and AR application. The use of AR application did not have a significantly higher influence than the computer-based multimedia module on residents' knowledge improvement, perceived usability, and acceptance. The reason behind the study results may be that the 3D interactive learning experience of AR was not much different enough to make a significantly greater impact on learner achievement compared with the multimedia module. Therefore, as future work, the author intends to develop an MR simulator based on the educational concept and the 3D modelling assets presented here. It would be interesting to investigate whether the fully immersive learning of MR simulator that is part of a TTE training programme will yield different, or greater, impact on learning achievement in trainee doctors compared with the computer-based multimedia module.

Additionally, the results can be associated with several previous studies stated that novel interactive 3D and immersive digital learning technologies are not always more effective than conventional—low-fidelity or less interactive—learning resources. In most learning situations, this phenomenon is related to a lack of instructional design strategy to balance students' cognitive load in digital media learning. Although 3D computer-generated interactive visualisation can aid learners to get a better understanding of complex educational contents, its excessive use can lead to increased learners' cognitive load and cause their frustration with digital learning activities. Therefore, the main lesson learned from this PhD study for future research is the importance of well-designed instructional strategy for developing 3D interactive digital media with a focus of reducing cognitive load in TTE learning. As mentioned, the ambition of the author is to develop an MR simulator for TTE education for future research. Lessons learned from this PhD study will benefit a future study design to develop the MR simulator which can provide the notable differences in some potential educational advantages over the conventional learning media. The author will consolidate insight gained from the study and produce recommendations for best practice in the development and evaluation of novel 3D interactive learning systems for TTE education that could be used by other researchers in the future.

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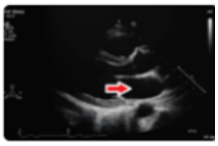
Appendix A

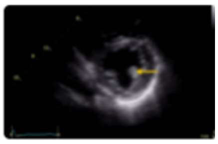
Multiple-Choice Questions for Basic TTE

Question Stems, Answers and Distractors		Knowledge Test
1. What view is shown in this video? A Parasternal short axis, mid papillary level B Subcostal 4 chamber C Parasternal long axis D Apical 4 chamber		Parasternal Short Axis
2. Which window is the image representing for? A Subcostal 4 chamber B Apical 4 chamber C Subcostal IVC D Apical 2 chamber	 	Subcostal 4 Chamber
3. The PSAX at the mid-papillary level shows all of the following **except:** A Right ventricle B Posteromedial papillary muscle C Left atrium D Left ventricle		Parasternal Short Axis
4. What structure is identified by the arrow? A PLAX, right atrium B Subcostal 4, left atrium C PLAX, left atrium D Subcostal 4, right ventricle		Parasternal Long Axis
5. The subcostal 4 view shows all of the following **except:** A Right ventricle B Right atrium C Aortic valve D Mitral valve		Subcostal 4 Chamber

Question Stems, Answers and Distractors	Knowledge Test

6. What window is this and what is the arrow pointing at?

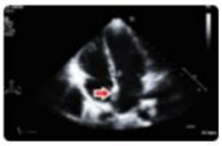
- **A** PSAX, anterolateral papillary muscle
- **B** PSAX, posteromedial papillary muscle
- **C** PLAX, anterolateral papillary muscle
- **D** Subcostal 4 chamber, posteromedial papillary muscle



Parasternal Short Axis

7. What window is this and what structure is identified by the arrow?

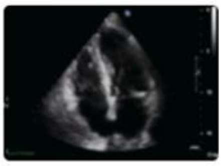
- **A** Subcostal 4, inter-atrial septum
- **B** Subcostal 4, left atrium
- **C** Apical 4 chamber, inter-atrial septum
- **D** Apical 4 chamber, inter-ventricular septum



Apical 4 Chamber

8. What window is this?

- **A** Apical 3 chamber
- **B** Apical 4 chamber
- **C** Subcostal 4 chamber
- **D** Parasternal long axis



Apical 4 Chamber

9. Which of the following structures can be **only found** in apical 4 chamber view?

- **A** Right upper pulmonary vein (RUPV)
- **B** Left ventricle
- **C** Mitral valve
- **D** Liver

Apical 4 Chamber

10. Which structure **is not shown** by this probe position?

- **A** Right ventricle
- **B** Aortic valve
- **C** Right atrium
- **D** Left ventricle

Parasternal Long Axis

11. Which window is the image representing for?

- **A** Subcostal 4 chamber
- **B** Parasternal short axis
- **C** Parasternal long axis
- **D** Apical 4 chamber

Apical 4 Chamber

Question Stems, Answers and Distractors	Knowledge Test

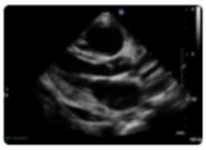
12. Which of the following is **false** about image acquisition of apical 4 chamber?

- A The probe marker is positioned to the patient's right shoulder
- B Place the probe in the 4th or 5th intercostal space
- C The probe marker is positioned to the patient's left
- D Place the probe near the midclavicular line

Apical 4 Chamber

13. What window is shown in this video?

- A Parasternal short axis, mid papillary level
- B Parasternal long axis (PLAX)
- C Apical 3 chamber
- D Apical 4 chamber



Parasternal Long Axis

14. Which of the following statements is **true** about image acquisition of PSAX at the mid-papillary level?

- A The probe marker is positioned at the right parasternal border
- B Make sure that all four cardiac chambers are shown
- C The index marker points towards the patient's right shoulder
- D Place the probe in the 3rd or 4th intercostal space

Parasternal Short Axis

15. Which window is the image representing for?

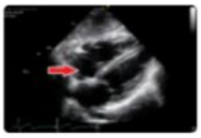
- A PSAX
- B Apical 4 chamber
- C PLAX
- D Subcostal 4 chamber

Parasternal Long Axis

16. Which of the following statements is **not true** about image acquisition of PLAX?

- A The probe marker is positioned towards the patient's right shoulder (11 o'clock)
- B The probe marker is positioned at the left parasternal border
- C Place the probe in the 4th or 5th intercostal space
- D A and C

Parasternal Long Axis

Question Stems, Answers and Distractors		Knowledge Test
17. What structure is identified by the arrow? A Left atrium B Right ventricle C Right atrium D Mitral valve		Subcostal 4 Chamber
18. Which window is the image representing for? A Parasternal short axis B Parasternal long axis C Subcostal 4 chamber D Apical 4 chamber		Parasternal Short Axis
19. What window is shown in this video? A Parasternal short axis, mid papillary B Subcostal 4 chamber C Parasternal short axis D Apical 4 chamber		Subcostal 4 Chamber
20. Which of the following statements is **not true** about image acquisition of subcostal 4 chamber? A The probe marker is positioned towards the patient's right shoulder B Place the probe in subxiphoid region of the abdomen C Make sure that all four cardiac chambers are shown D The probe marker points towards the patient's left (3 o'clock)		Subcostal 4 Chamber

Appendix B

Participant Information Sheet

Participant Information Sheet

You are invited to participate in this study, which is voluntary. This is a PhD project of the University of Birmingham. This document may contain the wordings that you might not understand, please ask the principal investigator or representative to explain until understanding. You may take the document to read at home or at any time to help making decision in participation.

Project title A Comparative Study for Learning Outcomes and Learning Experience by Using Augmented Reality Application and E-learning in Basic Knowledge of Transthoracic Echocardiography

Name of Principle Investigator: PhD student Miss Pansa Noiskul

Name of Co-investigators: Lead Supervisor Professor Peter Gardner

: Clinical Supervisor Professor Dr Ananya Boonyasirinant

Research site Faculty of Medicine Siriraj Hospital, Bangkok, Thailand

Affiliation and Telephone number of principle investigator which can be reached in and after office hours

(University) College of Engineering and Physical Sciences, University of Birmingham

(Workplace) Medical Educational Technology Center, Faculty of Medicine Siriraj Hospital

Source of funding Not applicable

Conflict of interest declare ☑ No ☐ Yes, specify……………………………………………………………………………..

Duration of research November 2020 – May 2021

Background/rationale

Transthoracic echocardiography (TTE) is a type of ultrasound that provides useful information in clinically assessing cardiac function. TTE is the most common use of cardiac imaging. Benefits of TTE over other types of echo (e.g., transoesophageal echocardiography or stress echo) include its non-invasive nature, painless, and capability to dynamically determine heart anatomy, function and volume status. Currently, TTE is not limited to be performed and interpreted by cardiologists. Because an advantage of TTE is providing accurate and rapid real-time data for diagnosis and treatment, several different medical specialists have started applying TTE in their routine clinical management in the perioperative setting, or critical care setting for past decade. Therefore, TTE has been widely used in many specialties including emergency medicine, surgery, anaesthesiology, or intensive care medicine.

Competency in TTE is the ability of medical professionals to integrate knowledge and skills that are essential to perform TTE examination. According to Bloom's taxonomy, learning process comprises of three domains: cognitive (knowledge), affective (attitudes), and psychomotor (skills). Throughout the literature, instructional designers, educators and experts often refer to two domains of learning within the framework of TTE curriculum which are cognitive domain and psychomotor domain. Basically, cognitive domain involves TTE baseline knowledge, such as details of normal and abnormal cardiac anatomy, how to interpret the acquired TTE images, and spatial understanding of transducer movements in relation to standard TTE windows. Whereas, the psychomotor domain refers to echo performance regarding the practical skill to obtain TTE views and optimise the image quality, including the technical expertise required to operate the echo machine.

Various types of educational technology are incorporated in echocardiography training, such as simulator, e-learning and video tutorial. Immersive technology is an umbrella term of new technology that covers several types of interactive experience regarding digital objects and physical environment integration. Augmented reality (AR) is a form of immersive technology that a physical world is overlaid with digital objects. Important benefits of educational technology in TTE training include enhancing learning engagement, promoting the ability of the learner to visualise cardiac anatomy, or providing the student with a simulated task of TTE to practice procedural skills before the examination with a real patient. Throughout the literature, the simulation-based learning and the web-based e-learning platform are the commonest materials used for echocardiography training, whereas very few studies mentioned the utilisation of immersive technology. Therefore, the educational benefit of immersive technology on the learning curve of basic TTE training is yet unidentified.

The researcher aims to develop two types of educational tools: an e-learning and an augmented reality application and incorporate these tools in self-direct learning activities for novice residents from several specialties. The main investigation of this study focusses on the effectiveness of novel technology like the AR application compared with the e-learning on the cognitive development of learners about basic knowledge of TTE.

Research objectives

- To develop two types of technology of learning resources (an augmented reality application and an e-learning) for basic transthoracic echocardiography education.
- To investigate whether and how an augmented reality application and an e-learning affect on cognitive domain of transthoracic echocardiography learning.
- To conduct the usability evaluation in effectiveness, efficiency and satisfaction of learners after educational activities with augmented reality application and e-learning.

.

You are invited to take part in the research owing to

- Thai doctors in Residency Training in Internal Medicine, or Fellowship Training in Cardiology at the Faculty of Medicine Siriraj Hospital

How many total of participants/ volunteers take part in the research

46 participants

If you decide to take part in the research, the steps of research will be as follows:

Note: All research activities below will not involve with testing on human subjects, medicinal product or patient

Phase 1: Cognitive assessment		
Duration	Steps	Activities
5 min	1.1	Give your demographic information (gender, age, and level of training) and fill in a paper-based questionnaire to identify your background, experience and attitude in echocardiography and immersive technology
20 min	1.2	Complete multiple-choice questions of pre-test about basic transthoracic echocardiography
20 min	1.3	You will be randomly assigned into group A or group B and will experience with the first session for self-direct learning with educational tools; Group A: Learning with a computer-based multimedia module Group B: Learning with an augmented reality application
20 min	1.4	Complete multiple-choice questions of post-test about basic transthoracic echocardiography
Phase 2: Usability evaluation		
20 min	2.1	Group A: Learning with an augmented reality application Group B: Learning with a computer-based multimedia module
10 min	2.2	Complete a set of paper-based form of satisfaction survey and usability evaluation

Note During participation in this study, you may be photographed and/or videotaped for the purpose of the research. We will notify you every time before taking photographs and/or recording videos. Your face in these photos and or videos will not be revealed or identifiable in any academic presentation, thesis or publication that result from the research. No one outside the research team will be allowed to access the original recording.

The risk that may occur when taking part in the research

Not applicable

If you decide not to join the project

Your intention of nonparticipation does not cause any negative effect on your study or training. You have the right to leave the study at any time for any reason.

If you have any inquiries regarding the research or if the unwanted side effect from the research occurs, you can contact Miss Pansa Noiskul, pansa.nois@gmail.com, 095-395-0901

Expected advantages from the research directly to the *participant*/volunteer and indirectly to the community as a whole in the future There will be no remuneration for your participation in this study.

The expenses that the participant/volunteer have to be responsible during taking part in the research
Not applicable

If there are additional informations both advantage and disadvantage involve in the research, the researcher will inform the participant immediately.

The personal data of the participant/volunteer will be kept confidentially and will not disclose to public individually. The report of research result is provided as whole information. It may be published on thesis or publication. However, the individual subject's data may be able to disclose for a body of person to investigator such as sponsor, auditing division of the government organization and Institutional Review Board Committee.

The subjects have a right to withdraw from the project at any time without giving advance notice or reason. Furthermore, the withdrawal of project will not affect the received treatment and services.

If you are not treated as stated in this participant information sheet, you can make a complaint to the SIRB chairman, Office of Siriraj Institutional Review Board, Room 210, 2nd floor of His majesty the King's 80th Birthday Anniversary 5th December 2007 Building, Telephone 66 2419 2667-72, Fax 66 2411 0162

Signature.. (Participant/Volunteer)

(...)

Date...

Signature. .... Researcher/Person taking the consent

(Miss Pansa Noiskul)

Date..

Appendix C

Consent Form

Consent Form

Date.................Month....................Year................

I..Age.............................years
Address at a residence no.................., Road................................, Sub-district ....,
District......................................, Province.., Post code......................................
Telephone......................................

Would like to give the consent to participate in the research project titled A Comparative Study for Learning Outcomes and Learning Experience of Resident Doctor by Using Augmented Reality and E-learning on Basic Echocardiography Education

I have acknowledged the background and purposes of this research, a detail of research process, the expected benefit and risk which may occur in taking part in the research, including the guidelines for protection and correction if the danger occurs, as well as the remuneration (specify if any) and the expenses I have to take responsibility. I have read the foregoing information and have had opportunity to ask questions about it and any questions that I have asked been answered to my satisfaction.

I consent voluntarily to participate as participant in the research.

If I have any questions about the research process, or the unwanted side effects from the research, I will be able to contact Miss Pansa Noiskul, Email: pansa.nois@gmail.com, Tel: 095- 3950901

If I have been treated differently from stated in the participant information sheet, or would like to discuss problems, concerns, questions or obtain information/ offer input, I can contact the SIRB chairman at the Office of Siriraj Institutional Review Board, Room 210, 2nd floor of His Majesty the King's 80th Birthday Anniversary 5th December 2007 Building, Telephone 66 2419 2667-72, Fax 66 2411 0162. Or if you would like to discuss problems, concerns, questions or obtain information/ offer input you can contact the HRPU office at the same address.

I have acknowledged the rights to obtain additional information on the advantage and disadvantage involve in the research and can withdraw from participating at any time without giving advance notice or reason. The withdrawal of project will not affect the received treatment and service in the future. I give the consent to the researcher to use my personal data obtained from the research, and these sources are not publicly available individually but should be provided as a whole information only.

Appendix D

Learning Needs Analysis Questionnaire

Participant ID: ☐☐☐ **Date:** ____________________

UNIVERSITY OF BIRMINGHAM

การศึกษาเปรียบเทียบผลลัพธ์ทางการเรียนรู้และคุณค่าทางประสบการณ์ในการเรียนรู้ของแพทย์ประจำบ้าน ที่เรียนด้วยแอพพลิเคชันแสดงภาพดิจิตอลสามมิติเสมือนจริง กับ บทเรียนออนไลน์ในเรื่องพื้นฐานเอคโค่คาร์ดิโอกราฟี (A Comparative Study for Learning Outcomes and Learning Experience of Resident Doctor by Using Augmented Reality and E-learning on Basic Echocardiography Education)

Learning Needs Analysis Questionnaire: แบบสอบถามความต้องการทางการเรียน

Part 1: Personal information

โปรดระบุความเชี่ยวชาญ/สาขาวิชาของท่าน
Please state your profession:

- ☐ หทัยวิทยา (cardiology)
- ☐ อื่นๆ ____________________

Position	**Age**	**Gender**
☐ Resident Doctor Year 1	☐ 18-25	☐ Male
☐ Resident Doctor Year 2	☐ 25-30	☐ Female
☐ Other ____________________	☐ 30-35	☐ Prefer not to say
	☐ 35-40	
	☐ 40-45	
	☐ Over 45	

Part 2: Background and experience in echocardiography

1. HAVE YOU EVER PERFORMED ULTRASOUND EXAMINATION?

☐ YES (please specify—e.g., lung, pregnancy, abdominal) ☐ NO

____

2. HAVE YOU HAD ANY EXPERIENCE WITH ECHOCARDIOGRAPHY?

☐ YES (Performing by myself) ☐ YES (Observing other people) ☐ NO

3. HOW IMPORTANT IS ECHOCARDIOGRAPHY TOWARDS YOUR FUTURE CAREER PATH?

- ☐ Not important
- ☐ Slightly important
- ☐ Important
- ☐ Very important
- ☐ No opinion / No decision yet

4. HOW FAMILIAR ARE YOU WITH AUGMENTED REALITY (AR) BEFORE THIS STUDY?

- ☐ I have never heard of it
- ☐ I have heard the word, but don't know what it is
- ☐ I know it as (please specify)

  ____

- ☐ I know it well, and have experience with it (please specify)

  ____

Appendix E

Questionnaires for Evaluating Usability, Satisfaction, and Acceptance

1. The System Usability Scale (SUS)

Participant ID: __ __ __

โปรดประเมิน Computer-based multimedia ด้านคุณค่าการใช้งาน ตามหัวข้อต่อไปนี้ (The System Usability Scale)

		1 **Strongly Disagree** ไม่เห็นด้วยอย่างมาก	2	3	4	5 **Strongly Agree** เห็นด้วยอย่างมาก
1.	I think that I would like to use this multimedia frequently.	○	○	○	○	○
2.	I found this multimedia unnecessarily complex.	○	○	○	○	○
3.	I thought this multimedia was easy to use.	○	○	○	○	○
4.	I think that I would need the support of a technical person to be able to use this multimedia.	○	○	○	○	○
5.	I found the various functions in this multimedia were well integrated.	○	○	○	○	○
6.	I thought there was too much inconsistency in this multimedia.	○	○	○	○	○
7.	I would imagine that most people would learn to use this multimedia very quickly.	○	○	○	○	○
8.	I found this multimedia very cumbersome to use.	○	○	○	○	○
9.	I felt very confident using this multimedia.	○	○	○	○	○
10.	I needed to learn a lot of things before I could get going with this multimedia.	○	○	○	○	○

Version 1.0, May 2020

Participant ID: __ __ __

โปรดประเมิน AR application ด้านคุณค่าการใช้งาน ตามหัวข้อต่อไปนี้ (The System Usability Scale)

		1 Strongly Disagree ไม่เห็นด้วยอย่างมาก	2	3	4	5 Strongly Agree เห็นด้วยอย่างมาก
1.	I think that I would like to use this AR application frequently.	○	○	○	○	○
2.	I found this AR application unnecessarily complex.	○	○	○	○	○
3.	I thought this AR application was easy to use.	○	○	○	○	○
4.	I think that I would need the support of a technical person to be able to use this AR application.	○	○	○	○	○
5.	I found the various functions in this AR application were well integrated.	○	○	○	○	○
6.	I thought there was too much inconsistency in this AR application.	○	○	○	○	○
7.	I would imagine that most people would learn to use this AR application very quickly.	○	○	○	○	○
8.	I found this AR application very cumbersome to use.	○	○	○	○	○
9.	I felt very confident using this AR application.	○	○	○	○	○
10.	I needed to learn a lot of things before I could get going with this AR application.	○	○	○	○	○

Version 1.0, May 2020

2. the Standardized User Experience Percentile Rank Questionnaire (SUPR-Q)

Participant ID: __ __ __

โปรดประเมิน Computer-based multimedia ด้านความพึงพอใจ ตามหัวข้อต่อไปนี้ (The Standardized User Experience Percentile Rank Questionnaire)

	Strongly Disagree ไม่เห็นด้วยอย่างมาก 1	2	3	4	**Strongly Agree** เห็นด้วยอย่างมาก 5
1. This multimedia is easy to use.	○	○	○	○	○
2. It is easy to navigate within this multimedia.	○	○	○	○	○
3. The information on this multimedia is credible.	○	○	○	○	○
4. The information on this multimedia is trustworthy.	○	○	○	○	○
5. How likely are you to recommend this multimedia to a friend or colleague?	○	○	○	○	○
6. I will likely visit this multimedia in the future.	○	○	○	○	○
7. I found the multimedia to be attractive.	○	○	○	○	○
8. This multimedia has a clean and simple presentation.	○	○	○	○	○

Version 1.0, May 2020

Participant ID: __ __ __

โปรดประเมิน AR application ด้านความพึงพอใจ ตามหัวข้อต่อไปนี้ (The Standardized User Experience Percentile Rank Questionnaire)

	Strongly Disagree ไม่เห็นด้วยอย่างมาก 1	2	3	4	Strongly Agree เห็นด้วยอย่างมาก 5
1. This AR application is easy to use.	○	○	○	○	○
2. It is easy to navigate within this AR application.	○	○	○	○	○
3. The information on this AR application is credible.	○	○	○	○	○
4. The information on this AR application is trustworthy.	○	○	○	○	○
5. How likely are you to recommend this AR application to a friend or colleague?	○	○	○	○	○
6. I will likely visit this AR application in the future.	○	○	○	○	○
7. I found the AR application to be attractive.	○	○	○	○	○
8. This AR application has a clean and simple presentation.	○	○	○	○	○

Version 1.0, May 2020

3. the Technology Acceptance Model (TAM)

Participant ID: __ __ __

โปรดประเมิน Computer-based multimedia ด้านการยอมรับสื่อ ตามหัวข้อต่อไปนี้ (The Technology Acceptance Model)

		Strongly Disagree ไม่เห็นด้วยอย่างมาก				**Strongly Agree** เห็นด้วยอย่างมาก
		1	2	3	4	5
1.	Learning to use multimedia would be easy for me.	○	○	○	○	○
2.	My interaction with multimedia was clear and understandable.	○	○	○	○	○
3.	It would be easy for me to achieve knowledge of basic TTE at the multimedia.	○	○	○	○	○
4.	Using multimedia would increase my learning effectiveness.	○	○	○	○	○
5.	Using multimedia would increase my productivity in transthoracic echocardiography training.	○	○	○	○	○
6.	Using multimedia would improve my performance of transthoracic echocardiography exam.	○	○	○	○	○
7.	I found the multimedia useful.	○	○	○	○	○
8.	I believe it is a good idea to use this multimedia in my residency/echocardiography training.	○	○	○	○	○
9.	I have a generally favourable attitude toward using multimedia.	○	○	○	○	○
10.	I think this multimedia should be a trend of multimedia material in transthoracic echocardiography training.	○	○	○	○	○
11.	I intend to use this multimedia during my residency training.	○	○	○	○	○
12.	I would love to use this multimedia during my residency training.	○	○	○	○	○
13.	I hope this multimedia should be provided in my residency training programme.	○	○	○	○	○
14.	I will inform others of the benefit of this multimedia for learning basic transthoracic echocardiography.	○	○	○	○	○

Version 1.0, May 2020

Participant ID: __ __ __

โปรดประเมิน AR application ด้านการยอมรับสื่อ ตามหัวข้อต่อไปนี้ (The Technology Acceptance Model)

		Strongly Disagree ไม่เห็นด้วยอย่างมาก				**Strongly Agree** เห็นด้วยอย่างมาก
		1	2	3	4	5
1.	Learning to use AR application would be easy for me.	○	○	○	○	○
2.	My interaction with AR application was clear and understandable.	○	○	○	○	○
3.	It would be easy for me to achieve knowledge of basic TTE at the AR application.	○	○	○	○	○
4.	Using AR application would increase my learning effectiveness.	○	○	○	○	○
5.	Using AR application would increase my productivity in transthoracic echocardiography training.	○	○	○	○	○
6.	Using AR application would improve my performance of transthoracic echocardiography exam.	○	○	○	○	○
7.	I found the AR application useful.	○	○	○	○	○
8.	I believe it is a good idea to use this AR application in my residency/echocardiography training.	○	○	○	○	○
9.	I have a generally favourable attitude toward using AR application	○	○	○	○	○
10.	I think this AR application should be a trend of multimedia material in transthoracic echocardiography training.	○	○	○	○	○
11.	I intend to use this AR application during my residency training.	○	○	○	○	○
12.	I would love to use this AR application during my residency training.	○	○	○	○	○
13.	I hope this AR application should be provided in my residency training programme.	○	○	○	○	○
14.	I will inform others of the benefit of this AR application for learning basic transthoracic echocardiography.	○	○	○	○	○

Version 1.0, May 2020