Investigating Digital and Three-Dimensional Approaches for Enhancing Human Anatomy Education

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By

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Abstract

The anatomical sciences form the cornerstone of clinical professions including medicine, surgery, and dentistry. Gross anatomy is essential for clinical examination, surgical procedures, and clinical image interpretation. Embryology provides basis for understanding fertility, antenatal care, and congenital abnormalities. Human anatomy and embryology are three-dimensional (3D) and visual disciplines, and anatomy education is increasingly delivered in a blended format. Therefore, it is important to identify effective 3D visualisation approaches for practical and remote delivery of anatomical education.

This project aimed to identify the topics and concepts of anatomy learning considered to be challenging by students, and to develop specific 3D visualisation learning activities to address these areas.

Learning approaches comprising an anatomy visualisation table, 3D-printed models, and remote digital resources were developed. A pragmatic mixed-methods approach was used to triangulate the value of learning activities. Pre-post and delayed experimental testing and Likert-type questionnaire items were analysed statistically to identify learner performance and perceptions. Significant improvements in learner interpretation of clinical images were identified when a combined visualisation table and 3D printed model activity was compared to a two-dimensional (2D) control ($P < 0.001$). Additionally, remote visualisation resources for gross anatomy learning were implemented, and significant improvements in student learning performance were identified ($P < 0.001$).

For each phase of the study, free-text questionnaire items were analysed by semi-quantitative content analysis, and deeper learner perceptions identified in phenomenological focus groups were analysed by qualitative thematic analysis. In general, learners had positive perceptions of new activities involving 3D anatomy and embryology resources when used in practical and remote learning environments.

These findings suggest that 3D synchronous multimodal resources and asynchronous 3D digital learning resources can enhance student abilities in clinical image interpretation and embryology learning. Thus, this work provides guidelines supporting the implementation of 3D visualisation strategies in medical and health curricula to improve student understanding of human anatomy education.

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Term	Definition
Spatial Understanding	The ability to understand an object in its own space.
Anatomical Features	Any human anatomical structure which includes visceral organs, systems, blood vessel, anatomical features of embryos, etc.
Plastinated	A technique in which anatomical structures as preserved by replacing the water and the fat with certain type of plastic. First developed by Gunther von Hagens in 1977 (Pashaei, 2010).
Prosection	A pre-prepared specimen of human cadaveric material produced by dissection for use as a learning and teaching resource
Neurophobia	The fear/anxiety and uncertainty of neuroscience, neurology, or clinical neurology experienced by learners (McCarron et al., 2014).
Carnegie Stages	The 23 stages after fertilisation that describe the development steps of the human embryo (Harkness and Baird, 1997).
3D image Segmentation	The process by which the region of interest is selected and isolated from the other regions in clinical images (CT or MRI) using software.

List of Abbreviations

Term	Definition
3D	Three-dimensional
3DP models	Three-Dimensional Printed Models
CT Scan	Computed Tomography
MRI	Magnetic Resonance Imaging
DICOM	Digital Imaging Communications in Medicine
PACS	Picture Archiving and Communication System
MLE	Medical Learning Environment
BCE	Before the Common Era
CE	Common Era
VT	Visualisation Table

Chapter 1. Introduction

1.1 History of Anatomy and Embryology Education

Anatomy is a cornerstone of all medical curricula and many medical science curricula, such as those in physical therapy, radiological sciences, and nursing. An understanding of gross anatomy courses is essential in medical education the for clinical professions (Böckers et al., 2010). Studying all the structures and systems of the human body, including the muscles, organs, nerves, and blood vessels, is a requirement for anatomy courses in medical, pharmacy, and nursing schools (Smith et al., 2016a; Connolly et al., 2018; Finn et al., 2018). Moreover, an understanding of anatomy is essential for clinical practice and specialties in terms of medical image interpretation, clinical examination, and surgical-skill development (Davis et al., 2014).

Anatomy education has markedly changed from the time of ancient Egypt (300 BCE) to the present, and the amount of information and its format varies depending on the demands of individual professions. Nonetheless, the content and methods currently used for teaching anatomy have not substantially changed in recent years (Siddiquey et al., 2009). Anatomy, one of the oldest disciplines in medicine, was developed over many years and civilisations (Habbal, 2017). A brief description of the history of anatomy education is presented in this part of the study to better understand its beginnings.

1.1.1 Ancient Egypt

According to the oldest records from around 300 BCE, the ancient Egyptians were the first to recognise medicine as a craft (Habbal, 2017). Additionally, the first recorded school of anatomy was in Alexandria in Egypt (Siddiquey et al., 2009). During the Egyptian era, physicians had only superficial anatomical information and knowledge based on drawings and sculptures (Porter, 1999). The Edwin Smith papyrus, the oldest known medical surgical document, was discovered in 1862 in Luxor, Egypt (Feldman and Goodrich, 1999; Stiefel et al., 2006). It suggests that ancient Egyptians had detailed information on anatomy and the treatment of certain parts of the human body (Stiefel et al., 2006; Adu-Gyamfi, 2015). The Edwin Smith papyrus indicates that Egyptian scholars had gained medical and surgical skills, some of which are the foundation of many modern surgical and treatment techniques (Stiefel et al., 2006). This document, written around 3000 BCE, provides insight into the medical practice of using eyepaint during that era (Feldman and Goodrich, 1999; Stiefel et al., 2006).

The papyrus includes lists of 48 medical cases, arranged by anatomical regions (e.g., the meninges, cranial structures, brain, and cerebrospinal fluid) and explains their diagnosis, examination, and treatment. The document also recognises body organs such as the liver, spleen, kidneys, heart, and vessels connected to the heart (Feldman and Goodrich, 1999; Stiefel et al., 2006). No evidence exists of human dissection by the Egyptians. However, the ancient Greek physician Herophilus performed dissection in an Alexandrian medical school and described many of the human body structures (Adu-Gyamfi, 2015). Some names of important bones were first described by the Egyptians, such as the collarbone (Adu-Gyamfi, 2015). At the time, dissection was performed mainly on animals and monkeys.

1.1.2 The Ancient Greeks

The Greek scientists were the first to develop a scientific approach to the field of anatomy (500–336 BCE) (Habbal, 2017). Many scientists contributed to anatomy during that era, but the work of Hippocrates (460–377 BCE) provided the main foundation for medicine and the format of the anatomical sciences (Siddiquey et al., 2009). Hippocrates wrote several books on anatomy, and his contribution provided an understanding of the functions of several organs, such as the kidneys (Siddiquey et al., 2009; Craik, 2014). Hippocrates conducted experiments and collected data demonstrating that diseases are caused by natural processes, and additionally attempted to understand medicine through facts and ideas rather than beliefs (Iniesta, 2011; Craik, 2014).

Aristotle (384–322 BCE), a Greek scientist, was the first to use the word ‘anatomy’, a Greek word meaning ‘cutting’ (Siddiquey et al., 2009). All early gross anatomy was identified by dissection, as a major method used to study the human body. Aristotle’s work contributed greatly to the understanding of comparative anatomy and embryology. Aristotle was the first scientist to dissect animals in a systematic manner (Habbal, 2017).

Herophilus (335–255 BCE) is widely acknowledged as the ‘father of anatomy’ for his important contributions to the field and observation of the human body (Bay and Bay, 2010). Herophilus was the first anatomist to perform systematic dissection and vivisection of the human body, and his work provided a clear understanding and knowledge of the nervous system, brain, liver, eyes, and reproductive system (Bay and Bay, 2010).

Galen (130–200 AD) was an ancient Greek physician who studied anatomy in Alexandria and then moved to Rome to seek further knowledge (Dunn, 2003; Siddiquey et al., 2009; Habbal, 2017). Galen was the most prominent anatomist during the Roman era (Dunn, 2003). The anatomy proposed by Galen was based mainly on the dissection of monkeys, and his work identified the importance of the neuromuscular system in terms of voluntary movements created through the action of muscles controlled by the brain via nerves and the spinal cord (Dunn, 2003). Galen also proposed that blood moves from the right side of the heart to the left, despite a lack of awareness of pulmonary circulation (Habbal, 2017). Galen's work provided explanations for many functions of human body parts that found longstanding acceptance until correction by later anatomists (Loukas et al., 2008; Markatos et al., 2019).

1.1.3 Anatomy in Medieval Islam

During the Middle Ages in Europe, the Islamic golden age occurred, involving the development of major sciences (701–1300 AD). Anatomy was one of the most developed fields during that period of time, and many Islamic scientists provided substantial input in several areas of anatomy, such as Ibn Al-Haytham, a Muslim scientist whose contributions to the fields of optics and vision made him 'the father of modern optics' (Tbakhi and Amr, 2007). Muhammad al Razi was an Islamic scientist who had extensive information of neuroanatomy and was the first to localise lesions in the nervous system and associate them with clinical symptoms (Shoja and Tubbs, 2007). The pulmonary circulation of the blood was first discovered and explained by Ibn Al-Nafis (Prioreschi, 2006; Loukas et al., 2008), thus forming the basis for an understanding of blood circulation through the body. The work of Ibn Al-Nafis corrected much of Galen's work on blood circulation, for example, by demonstrating that a Galenic foramina does not exist between ventricles (Prioreschi, 2006; Loukas et al., 2008). Much of the work by Muslim scientists during the Islamic golden age was translated into many languages at the start of the Renaissance period in Europe.

1.1.4 Andreas Vesalius and the foundation of modern anatomy

Anatomy continued to develop gradually until the 16th century, when the field saw extensive and rapid development (Habbal, 2017). The famous painter Leonardo da Vinci (1452–1519) made detailed anatomical illustrations and sketches, although his works have not been published (Zampieri et al., 2015). These sketches provided anatomical knowledge and information on inner human body structures that were useful in painting and sculpture (Jose, 2001). Later, these sketches were replaced by newer updated anatomical drawings (Jose, 2001).

In the 16th century, the work of the anatomist Andreas Vesalius (1514–1564), who has been called 'the father of modern anatomy', created its foundation (Da Mota Gomes et al., 2015; Zampieri et al., 2015). Vesalius was not influenced by da Vinci's work (Zampieri et al., 2015).

Vesalius obtained a doctorate from Padua University in Italy in 1537 CE. He investigated Galen's concepts to verify their accuracy (Zampieri et al., 2015). Vesalius initially based his knowledge on anatomy and physiology according to Galen. However, many of his dissections in Padua indicated that Galen had never dissected a human cadaver (Castiglioni, 1943; Zampieri et al., 2015). After several years of work, Vesalius published his masterpiece, *De Humani Coporis Fabrica*, in the summer of 1542 CE, thus marking a new era in anatomy and medicine worldwide (Zampieri et al., 2015). *De Humani Coporis Fabrica* was a new atlas of the human body (Cambiaghi, 2017). Vesalius worked with artists to create and draw illustrations and diagrams of human body parts to produce the first modern human anatomy atlas. He believed that images are important for teaching and learning human anatomy (Da Mota Gomes et al., 2015; Cambiaghi, 2017). Moreover, Vesalius's work focused on displaying human body parts in many dynamic positions to provide details regarding the body in motion (Da Mota Gomes et al., 2015).

The field of anatomy was developed on the basis of a combination of facts, assumptions, and exact science and information, forming the fundamental core of modern medicine (Tan and Yeow, 2003). The great discoveries and findings of Vesalius led to a complete reconsideration of the fields of not only human anatomy but also human physiology (Zampieri et al., 2015). The field of anatomy continued to develop until the 17th century, when human dissection became part of medical school education in most of Europe (Siddiquey et al., 2009; Habbal, 2017).

Moreover, the large public dissection displays that became famous during the 17th and the 18th centuries shifted to organised classroom dissection sessions (Ghosh, 2015). The printing revolution of the 18th and the 19th centuries enabled the printing and distribution of anatomy atlases, which provided new standards for studying human anatomy and the body (Siddiquey et al., 2009). Medical schools' growing demand for cadavers for dissection and medical purposes led to body snatching and encouraged murder to provide bodies for physicians and medical students to study (Ghosh, 2015; Burrows, 2019). Therefore, to manage the dissection process and body donation, laws and legislation were created and passed in many countries. In the United Kingdom, the Anatomy Act was passed in 1832 to allow medical schools to receive unclaimed and donated corpses for dissection by licensed anatomists and physicians for anatomical and sciences purposes (Ghosh, 2015; Hutton, 2015; Burrows, 2019).

Throughout history, many scientists and anatomists have provided extensive input in developing the field of anatomy. The first edition of *Gray's Anatomy* was published in 1858, thus strongly influencing the anatomy education and providing physicians, surgeons, and medical students with rapidly accessible, affordable teaching and learning resources (Standring et al., 2005). The development of new technologies, such as X-ray, computed tomography (CT) and magnetic resonance imaging (MRI), enabled anatomy and medicine to grow and develop. As anatomy became an important subject in medical curricula, the extents to which anatomy information and education are necessary in medical curricula were debated (Turney, 2007; Sugand et al., 2010).

1.2 Modern Context of Anatomy and Embryology Education

Over the past 20 years, anatomy education has been developed and updated for the 21st century (Smith et al., 2017). Lectures, full cadaveric dissections (the process of separating or cutting body tissues), anatomical models, and prosections (the process of dissecting a cadaver or part of a cadaver) are now considered traditional methods of teaching anatomy (Sugand et al., 2010; Li K, 2017). For example, anatomy teaching at Newcastle University currently involves practical sessions with prosected human cadaveric specimens, accompanied by lectures and other resources (Backhouse et al., 2017). Cadaveric dissection is considered one of the most effective methods for teaching anatomy (Chapman et al., 2013). Dissection sessions provide students with hands-on experience and promote teamwork, time management, and even coping with stress (Böckers et al., 2010).

Teaching approaches have been influenced by the introduction of new curricula in some universities, thus substantially decreasing teaching time, including the time allocated to anatomy (McKeown et al., 2003). At Newcastle University, the hours of contact time in the dissection room (DR) allocated for teaching anatomy in MBBS year one has been reduced from 26 to 10 hours per year in the integrated case-based curriculum that was launched for the 2017/18 academic year (Backhouse et al., 2017). Furthermore, the already limited time available to deliver clinically relevant embryology teaching for the medical degree programme has decreased, primarily because a greater focus is being placed on self-directed learning (Dyer and Thorndike, 2000; Aziz et al., 2002; Bergman et al., 2008; Sugand et al., 2010). Potential increases in the numbers of students admitted to these programmes may decrease the time spent in the DR. All these aspects have been considered by other medical schools in the UK, such as Brighton and Sussex Medical School, University of Sussex and Brighton (Smith et al., 2017), and overseas, such as Macquarie University and Western Sydney University in Australia (AbouHashem et al., 2015).

Although self-directed study using prosected specimens is encouraged, this activity is limited by the large numbers of students and the time available for each individual student to make use of the anatomy laboratories. Despite being important aspects of anatomy and embryology learning, clinically relevant anatomical variations (e.g., heart right/left dominance and the branching point of the sciatic nerve) and pathologies and congenital embryological abnormalities are not readily visible to medical students in human tissue or plastic models. Moreover, students must be able to make use of physical three-dimensional (3D) learning approaches for anatomy and embryology (Daniel et al., 2016) in addition to two-dimensional (2D) and non-visual methods such as online resources, paper handouts and practical guides, clinical images, lectures, and practical demonstrator teaching (Trelease, 2016). Although human cadaveric specimens are important for teaching medical students anatomy and pathology (Ramsey-Stewart et al., 2010; Sugand et al., 2010; Chapman et al., 2013), the use of novel alternative methods is also necessary. Such alternative approaches can enhance engagement, increase the variety of available resources (Johnson et al., 2012), and optimise understanding of anatomy through the use of effective learning tools (Chapman et al., 2013; Backhouse et al., 2017).

1.3 Clinical Imaging in Anatomy Education and Its Importance for Physicians and Medical Students

The important role of radiological and clinical images in medical curricula is recognised by medical educators (Relyea-Chew and Chew, 2007; Gunderman and Stephens, 2009). The integration of radiology within anatomy education and its importance are not new concepts; the importance of radiology in anatomy education is indicated in the literature as early as 1927 (Bardeen, 1927). An excellent understanding of anatomy and radiological images is important, because all physicians from all specialties must apply anatomical knowledge in interpreting clinical images to provide diagnoses (Sadler et al., 2018).

Pre-clinical radiology teaching for medical students should be well developed to prepare them for clinical practice and diagnosis, and to teach them the clinical relevance of the anatomy learned in the DR and lectures (Phillips et al., 2013a; Sadler et al., 2018). Junior physicians and medical students should receive an appropriate amount of clinical-imaging training in radiology integrated with gross anatomy teaching.

Educational value is likely to be enhanced when learners study the methods of a variety of disciplines, including clinical imaging and radiology, alongside their anatomy education (Ward and Walker, 2008a; Eagleton, 2015). In most medical curricula, clinical-imaging teaching and learning are commonly integrated within gross anatomy curricula and teaching (McLachlan, 2004; Miles, 2005; Nyhsen et al., 2013; Al Qahtani and Abdelaziz, 2014; Keenan and ben Awadh, 2019a). The teaching of radiology in medical curricula must provide appropriate knowledge and information to medical students regarding the various radiological tests and examinations that are appropriate or necessary for different clinical examinations and diagnoses (Gunderman and Stephens, 2009). Additionally, appropriate radiological knowledge and clinical-image-interpretation skills are necessary to diagnosis diseases and, in some cases, to identify potentially fatal conditions, such as pneumothorax or pulmonary embolisms, which require rapid response and treatment (Gunderman and Stephens, 2009; Al Qahtani and Abdelaziz, 2014).

Combining radiological and clinical-imaging with anatomical learning can increase student engagement, understanding, and knowledge acquisition (Dettmer et al., 2010; May et al., 2013; Slon et al., 2014), as well as improve their clinical-image-interpretation skills and anatomy test scores (De Barros et al., 2001; Chew et al., 2020). Clinical-imaging and radiological training are important for enhancing medical students' experience and understanding in learning challenging and important anatomical topics and concepts across all specialties, as supported by the Royal College of Radiologists in the UK (RCR, 2020b).

Early exposure of medical students to clinical-imaging interpretation and radiology allows them to become more confident in interpreting the results of radiological exams that they will see later in their professional careers and provides a better understanding of certain concepts in radiology and anatomy (Branstetter et al., 2007). In the UK, most medical schools have increased the amount of radiological anatomy in their medical curricula, and some involve radiologists in anatomy teaching (Sadler et al., 2018). Moreover, most of the anatomy departments in the UK have expressed great interest in increasing the use of radiological and clinical-image components in their courses (Sadler et al., 2018).

Radiological anatomy is a tool to aid the learning and understanding of dynamic and functional anatomy, and it can be integrated with traditional teaching methods including lectures and dissection, to provide educational benefits (Phillips et al., 2013a; Sadler et al., 2018). Radiological and clinical-imaging interpretation can be challenging for medical students studying anatomy; thus, providing medical students with appropriate resources to enhance radiological knowledge and clinical interpretation is important (Ben Awadh et al., 2019; Ben Awadh et al., 2022).

1.4 Embryology in Medical Education and the Importance of Embryology Education for Physicians and Medical students

Embryology is the study of an organism's development from fertilisation to the foetal stage (Brenton et al., 2007). Understanding the stages of embryonic development and the anatomy at each stage provides an important basis for learning and understanding the pathogenesis of congenital defects and fertility, which is an important topic in medical curricula (de Bakker et al., 2012). Embryology is a crucial part of medical curricula for understanding normal and abnormal human body development and thus providing appropriate clinical and surgical treatment of malformations (Sadler, 2019). Moreover, embryology is an essential and growing area in medical fields because birth defects are the main cause of infant mortality (Carlson, 2002; Petrini et al., 2002; Scott et al., 2013), accounting for 21% of infant deaths in Brazil in 2010 (Moraes and Pereira, 2010), while congenital abnormalities are the second main cause of infant deaths in the United Kingdom (Kurinczuk et al., 2010). Because of this elevated mortality rate, embryology education is an important part of medical curricula (Moraes and Pereira, 2010). Furthermore, embryology education provides a foundation for understanding the logical basis of the organisation of human body parts and organs, as well as how they are formed (Carlson, 2002).

Although embryology is important, it is receiving less attention in the medical curricula of some medical schools (Carlson, 2002; Scott et al., 2013). The introduction of new aspects of medical curricula, such as problem-based learning, in some medical schools has resulted in as much as an 80% decrease in the time dedicated to anatomy education, thus affecting embryology teaching (Scott et al., 2013).

The lack of professional teachers and instructors available to teach anatomy, and the cost of running a full cadaveric dissection session, have resulted in decreased time available for anatomy education (Scott et al., 2013). Additionally, embryology is considered a difficult subject for medical students (Kramer and Soley, 2002). Students tend to find visualising the structures particularly difficult, and they need more resources to assist them in 3D visualisation to understand 3D representations of embryonic structures (Kramer and Soley, 2002). The difficulty in visualising and understanding 3D representations of the anatomy of developing embryos has been reported by students, who may lack understanding of related topics and concepts (Moraes and Pereira, 2010).

The rapid 3D changes that occur during organ development make embryology difficult to teach and understand (Moraes and Pereira, 2010). Regardless of the 3D representation of anatomy and embryology (Sharpe, 2003), traditional teaching resources, including textbooks and PowerPoint presentations, are limited visual aids that tend to be in 2D. However, the ability to view the organisation of biological structures in 3D is important to enhance understanding of embryonic development (Sharpe et al., 2002a; Sharpe, 2003).

1.5 Alternative Teaching Resources and the Limitations of Traditional Teaching Methods

The most effective alternatives can be implemented without the limitations of cos, staff time, and donor availability associated with the use of cadaveric material, and without reduction in contact time. The introduction of digital applications such as e-learning has enhanced learning for students (Trelease, 2016), thus demonstrating that new methods can greatly affect students' understanding. An anatomy curriculum with multimodal methods of teaching can provide added value for students (Johnson et al., 2012). Furthermore, financial considerations in maintaining full cadaveric dissection sessions, and safety considerations regarding exposure of students and staff to harmful materials (e.g., formalin) are matters of concern for anatomy departments and medical schools (McMenamin et al., 2014). High-quality anatomy models are very expensive. For example, a thorax model containing the lungs and heart can cost £738.00 (Adam, Rouilly Limited), and students cannot remove these models from the DR for self-directed study. Furthermore, the availability of human cadavers can present a problem, and it is limited in some countries by legal, ethical, and religious constraints (Chapman et al., 2013; Preece et al., 2013; Smith et al., 2017).

Therefore, traditional anatomy and embryology teaching methods have practical limitations when used to educate undergraduate and postgraduate medical science students. Furthermore, informal conversation and interaction with medical students has identified particularly challenging concepts for students during learning of anatomy and embryology that relate to the difficulties experienced in the understanding of 3D anatomical structures and the interpretation of clinical images. Therefore, introducing effective learning resources that address all these needs is important. Current technological approaches can offer many advantages and benefits for both students and educators; for example, the use of three-dimensional printing (3DP) can enhance student understanding of challenging topics (Li et al., 2015; Lim et al., 2016).

1.6 Digital and 3D Resources in Anatomical and Medical Education

The main aim of implementing digital, 3D, and multimodal learning approaches in anatomical and medical education is to enhance students' understanding and learning of relevant anatomy that they can relate to clinical cases (Keenan and ben Awadh, 2019a). Additionally, many benefits of using both physical models and 3D digital images have been proposed (Preece et al., 2013; Wainman et al., 2018; Wainman et al., 2020). Cognitive visualisation can be supported by the spatial location of 3D objects and 2D images (Wu et al., 2012), and a link has been demonstrated between anatomical learning and visuo-spatial ability (Rochford, 1985; Garg et al., 2001; Nguyen et al., 2012; Vorstenbosch et al., 2013; Nguyen et al., 2014; Langlois et al., 2015; Langlois et al., 2017; Langlois et al., 2020). Because of a lack of resources, students usually depend on textbooks and lectures that provide only 2D representations of human anatomy, thus decreasing knowledge retention (Preece et al., 2013). Thus, determining and designing practical teaching resources to support the delivery of learning activities and objectives that fulfil the intended criteria are important. Additionally, digital and 3D resources can offer an applicable platform for applications that present digital 3D and cross-sectional anatomical and clinical images, such as CT scans (Keenan and ben Awadh, 2019a).

A variety of digital technologies and 3D anatomy visualisation resources are used to enhance teaching and provide understanding of clinical images and anatomical structures, including Sectra (Sectra AB, Linköping, Sweden) and Anatomage (Anatomage Inc., San Jose, CA) visualisation tables (VTs). Many research studies have shown the benefits and specific value of using VTs (Paech et al., 2017; Ward et al., 2018; Keenan and ben Awadh, 2019a; Shi et al., 2019) and other 3D visualisation technologies (Yammine and Violato, 2015).

The Sectra visualisation table (Sectra) is a large interactive screen that enables interaction with 3D human body images and CT or MRI scans (Sectra, 2021a). The Sectra visualisation table allows students to interact with and manipulate 3D human body images, as well as CT or MRI scans, for better understanding of the 3D aspects of the human body (Barrack et al., 2015). Moreover, Sectra provides many institutions and hospitals worldwide with real-life clinical data, some of which were obtained from real patients; although all patient information is kept anonymous to avoid any legal or ethical issues (Sectra, 2021a). Sectra also allows users to customise and securely store cases for teaching purposes. Cases of normal anatomy, pathology, trauma, surgery, and other specialties are stored in Sectra and can be manipulated for teaching purposes (Sectra, 2021a). Connecting to the cloud allows teachers and students to access a large library of medical cases for visualisation and modification. Another major advantage is that the Sectra network allows institutions to share cases and information with other Sectra users in institutions worldwide (Sectra, 2021a).

Furthermore, 3DP models continue to grow in popularity. Previous work has indicated the benefits of implementing this technology in anatomy teaching to support and enhance the understanding of anatomical structures (Drake and Pawlina, 2014; AbouHashem et al., 2015; Keenan and ben Awadh, 2019a). Moreover, many previous studies have described the benefits of implementing 3DP models that enhance student performance and instil positive perceptions of anatomy education (Lim et al., 2016; Smith et al., 2017; Fleming et al., 2020). The use of 3DP models outside the DR can provide a pedagogical benefit as a self-directed learning resource (Smith et al., 2017) and can help with the presentation of specific pathologies (Li K, 2017).

3D printers can produce accurate models with sufficient detail at low cost, thus decreasing the long-term costs of buying anatomical models (McMenamin et al., 2014; Smith et al., 2017). Additionally, many benefits of using both physical models and 3D digital images have been proposed (Preece et al., 2013; Wainman et al., 2018; Wainman et al., 2020). Furthermore, cognitive visualisation can be supported by the spatial co-location of 3D objects and 2D images (Wu et al., 2012), and a link has been demonstrated between anatomical learning and visuo-spatial ability (Rochford, 1985; Garg et al., 2001; Nguyen et al., 2012; Vorstenbosch et al., 2013; Nguyen et al., 2014; Langlois et al., 2015; Langlois et al., 2017; Langlois et al., 2020).

The new generation of students is highly familiar with the use of technology and readily employs it to enhance their study experience (Svirko and Mellanby, 2008). The use of e-learning resources is growing and has shown benefits in teaching complex and difficult topics (Morgulis et al., 2012). Thus, e-learning resources can enhance anatomy education by helping students improve and gain an appreciation of spatial relationships (Yeung et al., 2011). Additionally, self-directed learning resources can provide substantial value in medical education by encouraging students to be responsible for their own learning (Keenan and ben

Awadh, 2019a). Self-directed learning resources are most effective when used as part of a blended learning approach combined with other teaching methods, such as lectures (Jayakumar et al., 2015). The use of e-learning resources such as interactive online tutorials can be effective in delivering visual anatomical learning (Backhouse et al., 2017). The Sectra Education Portal (SEP; Sectra AB, Linköping, Sweden) is an example of a self-directed learning resource that students can access remotely to view anatomical and clinical cases (Sectra, 2021b). A full explanation of the SEP is provided in detail in the Methods chapter.

Typically, embryology is taught through lectures, textbooks, and labelled illustrations and figures (Lu, 2010). However, using just textbooks has limitations because they are static (Huang, 2005) and cannot represent the dynamic processes of embryonic development in 3D or show how structures change over time (Carlson, 2002). The use of digital embryology resources enables more effective learning than existing methods of teaching (e.g., lecture based). The use of multimedia resources in embryology teaching can enhance students' performance and long-term retention (Marsh et al., 2008; Moraes and Pereira, 2010). The introduction of a 3D atlas during lectures and learning activities that demonstrate the spatial relationships between developing organs and how these change throughout the embryonic period can enhance students' learning experience (Chekrouni et al., 2020).

1.7 Evaluation of the Impact of Digital and Three-Dimensional Resources in Anatomical and Medical Education

Digital and three-dimensional resources have been used in recent years to enhance anatomy education (Keenan and Ben Awadh, 2019b; Ben Awadh et al., 2022). These resources allow students to engage in flexible learning, in which resources, such as SEP and 3DP models, are accessed at times and locations that suit student schedules and learning (Pickering and Joynes, 2016). Because digital and three-dimensional resources are widely used in education, their impacts on education and their benefits to learners must be evaluated (Pickering and Joynes, 2016). Many evaluation frameworks have been well documented in the literature, but most evaluations have focused on programmes or individual resources within a course (Pickering and Joynes, 2016). Therefore, the technology-enhancing learning evaluation model (TELEM) was chosen here, because it can be applied to multiple disciplines, and was developed on the basis of experience in evaluating technology-enhanced learning resources in medical education (Pickering and Joynes, 2016). The TELEM contains four main levels that are used to investigate and evaluate resource impact on individuals and benefits for institutions (Pickering and Joynes, 2016). The first is level 0, which involves preliminary evaluation of the need for resources. At this level, an evaluation of the need for TEL resources should be performed before the resources are implemented in a course. This step can be achieved by gathering information through module evaluation, and staff experiences and opinions (Pickering and Joynes, 2016). Level 1, the second level in the TELEM, is divided into two areas: level 1a (learning satisfaction) and level 1b (learner gain) (Pickering and Joynes, 2016). Level 1a is an important learning tool involving evaluation of user stratification through a Likert-type questionnaire or focus group, to ensure user satisfaction and increase user engagement (Pickering and Joynes, 2016). Level 1b of the evaluation model measures the degree of learner gains between the TEL resources and existing resources through pre-tests and post-tests (Pickering and Joynes, 2016), and additionally measures the potential for knowledge gain. Level 2 focuses on learner impact, to understand the ability of resources to enhance learner gain and outcomes in specific teaching settings, such as modules, courses or practical sessions (Pickering and Joynes, 2016). This level can be verified with Likert-type questionnaires, focus groups, assessment data and usage details. Through level 2 analysis, the effectiveness of the TEL resources in relation to learner gain, impact and satisfaction can be well established (Pickering and Joynes, 2016). Level 3, the final step in the TELEM, focuses on institutional impact, which can be determined through a cost-feasibility study including investment analysis of the effects of the TEL resources on stakeholders (Pickering and Joynes, 2016). The information obtained from level 1 can correlate the costs with the benefits of implementing TEL resources to enhance education.

1.8 Implications of Threshold Concepts in Human Anatomy Education

There have been concerns among educators regarding why some students within a cohort may struggle with certain topics or points in the curriculum, whereas other students can simultaneously achieve effective understanding in these areas(Land et al., 2005). Understanding variations in student understanding and performance, and the underlying reasons for such discrepancies, is important to help students overcome these barriers to their learning (Land et al., 2005; Meyer and Land, 2005; Meyer et al., 2010). Consequently, a new perspective termed 'threshold concepts' arose, which is described as "akin to a portal, opening new and previously inaccessible way of thinking about something" (Meyer and Land, 2003). A threshold concept is defined as a troublesome aspect of knowledge or a specific topic within a particular subject (Meyer and Land, 2003; Land et al., 2005; Meyer et al., 2010). It is proposed that threshold concepts theory can transform the interpretation, understanding or viewing of new topics in which students cannot progress (Meyer and Land, 2005).

Furthermore, threshold concepts link subjects together, to enable learners to process their understanding of new subjects within the wider discipline. The comprehension and interpretation of the concept give students new insights into understanding a discipline or subject as a whole. Irreversible (in which the subject is unlikely to be forgotten once it is understood), transformative (in which a substantial shift in understanding of a subject occurs), and integrative (in which the interrelatedness of a previously hidden part of the topic is shown) qualities are defined as the main characteristics of threshold concepts (Land et al., 2005; Meyer and Land, 2005). In crossing the threshold, some fluctuations and oscillations in understanding between the 'pre-liminal' state and fully transformed states can occur, in which students can become stuck in an intermediate state that involves struggles between earlier understanding and failing to reach full understanding; this is defined as the 'state of liminality' (Meyer and Land, 2003; Land et al., 2005). The state of liminality can cause students to become less confident and more frustrated, and may result in learners abandoning their attempts to understand (Land et al., 2005). Thus, an appreciation of threshold concepts theory is important to ensure that students are provided with the necessary knowledge that is required to reach the transformed state. Moreover, crossing the threshold requires the integration of the new concept with prior understanding and knowledge. The concept of anatomical variations, in which individual people have anatomy variations different from the anatomy shown in textbooks, may be an example of the threshold concept, which clinicians must understand in order to safely perform clinical examinations, diagnosis, and surgery.

1.9 Association Between Spatial Ability and Human Anatomy Education

Spatial ability can be defined as the capacity to mentally combine and manipulate objects in three dimensions (Vandenberg and Kuse, 1978; Lufler et al., 2012). Spatial ability includes several components: the understanding of spatial relationships (spatial relations), object recognition, mental rotation of objects, and identification and manipulation of two- and three-dimensional representations (visualisation) (Carroll, 1993). Spatial ability is likely to be important for medical students, because many clinical procedures and clinical examinations require understanding of the human body in three dimensions (Sweeney et al., 2014). Spatial ability plays a major role in anatomy learning, particularly the anatomical structures in different positions and directions (Garg et al., 2001). Mental rotation is an important skill for understanding human anatomy structures in different planes. Mental rotation is a cognitive manipulation and rotation for stored images in the brain that can be used for problem-solving or spatial understating of a certain object in 3D (Guillot et al., 2007). Mental rotation ability can be measured through mental rotation tests (Lufler et al., 2012). Moreover, Mental rotation ability is positively influenced by anatomy learning, because of the ability to understand the 3D nature of the human body (Garg et al., 2001; Guillot et al., 2007; Lufler et al., 2012). The mental rotation test predicts the effectiveness of the digital and the 3D resources in facilitating student understating and learning of human anatomical structures. Additionally, digital resources and 3D models can enhance and improve the spatial ability of students who show weakness in mental rotation tests (Sweeney et al., 2014).

1.10 Effects of COVID-19 on Practical and Remote 3D Anatomical Learning

In December 2019, the World Health Organisation classified COVID-19 as a high-risk infectious disease worldwide after many cases had been reported in Wuhan, China (Zhu et al., 2020; Keenan et al., 2022). By March 2020, the World Health Organization declared COVID-19 a pandemic, and most countries, including the UK, took action to protect communities and prevent the spread of the disease (Mahase, 2020). The COVID-19 pandemic has affected learning in most educational institutions, particularly anatomy education, because many educational institutions followed governmental advice and regulations by taking measures to reduce the spread of coronavirus (Longhurst et al., 2020; Iwanaga et al., 2021). In many countries worldwide, schools and educational institutions at all levels were closed for a period of time to prevent the spread of the virus (Longhurst et al., 2020). For example, on the 16th of March 2020, Newcastle University stopped all face-to-face classes; suspended all non-essential work in all its research environments; and moved all teaching online, with communication largely restricted to email and video conferencing (Keenan et al., 2022). The new governmental regulations, such as social distancing, did not allow students access to cadavers or DRs, which have been the main learning venues for anatomy since the 17th century (Ahmed et al., 2020; Franchi, 2020; Harmon et al., 2021; Iwanaga et al., 2021). During the pandemic, medical schools could not hold full cadaveric dissection sessions, and the use of cadaveric materials such as prosections decreased (Harmon et al., 2021).

At the onset of the COVID-19 outbreak, anatomy educators were required to make many changes to traditional teaching methods and find appropriate alternatives, within days in some cases (Ahmed et al., 2020; Longhurst et al., 2020; Iwanaga et al., 2021). During and after the COVID-19 pandemic, the need arose to rapidly transition to remote and distance learning, as well as blended learning using technology resources to enhance anatomical learning (Longhurst et al., 2020; Iwanaga et al., 2021; Papa et al., 2022). Before the pandemic, the time available for anatomy teaching had been reduced and limited in some medical schools, thus compromising anatomy education (Zhang et al., 2019). This reduction in anatomy education had been debated before the pandemic and, owing to the pandemic, a need arose to ensure maintenance of appropriate anatomical learning and education through the implementation of new teaching resources and strategies (Longhurst et al., 2020; Harmon et al., 2021). The new educational resources and teaching strategies for anatomy education affected many students, including approximately 20,000 medical students throughout the United Kingdom and the Republic of Ireland (Longhurst et al., 2020).

Many resources were used by anatomy educators in the United Kingdom and worldwide during the pandemic to provide appropriate anatomical learning and education and to avoid poor-quality learning experiences for students (Evans et al., 2020; Longhurst et al., 2020; Harmon et al., 2021; Papa et al., 2022).

Microsoft Teams, Google Hangouts, Zoom, and other video conferencing applications were used during the pandemic to deliver live anatomy sessions and lectures for medical students (Longhurst et al., 2020; Moszkowicz et al., 2020). Teaching was delivered in the form of pre-recorded lectures and learning activities that were uploaded to university portals, such as the medical learning environment (MLE), to ensure good learning outcomes for students (Longhurst et al., 2020).

Normal sessions had been performed in the DR with cadaveric material. However, during the pandemic, some universities used digitised cadaveric resources (e.g., Acland Videos Atlas of Human Anatomy or YouTube videos); 3D virtual resources (e.g., Complete Anatomy and Sectra); or a combination of resources (Longhurst et al., 2020). In other medical institutions, live practical tutorials from DRs were delivered through software such as Zoom, which enabled the use of cadaveric materials in delivering practical session materials (Longhurst et al., 2020). Some universities performed online assessments with online 2D images via assessment software (e.g., ExamSoft) to evaluate student performance (Harmon et al., 2021). Online multiple choice questions, matching questions, and best answer questions have been used to assess students (Longhurst et al., 2020).

A benefit from the COVID-19 pandemic has been that universities were given opportunities to develop new remote learning resources for anatomy teaching (Franchi, 2020; Harmon et al., 2021; Ortadeveci et al., 2021; Singal et al., 2021; Papa et al., 2022). Additionally, most students have positive perceptions and motivations when using new technological resources such as virtual reality (VR) and augmented reality (AR) in learning anatomy (Iwanaga et al., 2021; Papa et al., 2022). During the COVID-19 pandemic, these new digital and 3D resources provided students with 3D views of anatomical structures, thus enabling better understanding of anatomy (Iwanaga et al., 2021). Reduced student engagement and limited teacher–student relationships are considered a drawback of these new resources (Longhurst et al., 2020). The implementation of new resources for anatomy education during the COVID-19 pandemic required careful integration with traditional teaching resources to provide students with the best educational resources to enhance their learning of anatomy (Papa et al., 2022).

Chapter 2. Educational Theory and Conceptual Framework

2.1 Theoretical Underpinnings

Cognitivism earning theories can provide a conceptual framework for understanding how the brain processes and formulates new information into understanding (Dennick, 2014). Therefore, such theories can provide insights into student learning of human anatomy and clinical-image interpretation. Cognitivism theory can be divided into two major categories: cognitivist theory and constructivist theory. The main constructivist concept proposes that understanding depends on the specific knowledge foundation and cognitive function of individuals when engaging in learning activities (Dennick, 2014).

David Ausubel has made considerable contributions to constructivism theory and education (Ausubel, 2012; Dennick, 2012, 2014, 2016). Ausubel's cognitive constructivism theory describes how knowledge is developed and retained by building on prior knowledge that may be associated with student experiences and backgrounds (Ausubel, 2012). Ausubel has proposed that the main factor in learning is what learners already know, and has also highlighted that learning is a constructive and building process rather than just a teaching process (Dennick, 2014). This statement not only highlights that learning is a building or constructive process, it also locates the learner (student), rather than the teacher, at the centre of the learning process (Dennick, 2014). The constructivist approach is a learner-centred approach in which the learner's needs, rather than the teacher's recommendations, are essential in designing pedagogical methods. Linking neuroscience to constructivist theory, brain studies have shown that repeated presentation of information or knowledge strengthens neural networks, thus resulting in more rapid neural responses (Schunk, 2012). 18rom a cognitive neuroscience perspective, the learning process involves forming and strengthening neural networks and connections, (Schunk, 2012). A summary of the framework of the constructivist theory as suggested by Dennick is presented in **Table 2.1**. Moreover, students are likely to initially gain a foundation in 3D anatomy before being introduced to gross anatomy structures in cross-sectional clinical images. On the basis of the constructivist framework (Dalgarno, 2002; Ausubel, 2012; Dennick, 2014), students may cognitively form an understanding of the position, size, appearance, and relationships between anatomical structures and features in clinical cross-sectional images on the basis of their existing knowledge and experience of the same structures and features in 3D. The implementation of 3D resources with 2D cross-sectional images is likely to accelerate this process by providing students with support in their observations, thereby enabling cognitive access to their prior 3D knowledge and understanding (Keenan and Powell, 2020).

Lev Semenovich Vygotsky has attempted to explain and study human thought in different ways (Vygotsky and Cole, 1978; Schunk, 2012), and has emphasised the social environment as the centre of development and learning (Schunk, 2012). Vygotsky has contributed to social constructivism theory (Vygotsky and Cole, 1978) by stating that constructivist learning is a social and cultural process facilitated by culture, language, symbols, social interactions, and the role of the teacher (Dennick, 2014; Akpan et al., 2020). Vygotsky also argued that learning is not an individual event but a result of social interaction (Dennick, 2014; Amineh and Asl, 2015).

The zone of proximal development, in which the learner can be supporting in creating knowledge and understanding through the support of experienced teachers and peers in educational and teaching interventions, is a concept developed by Vygotsky (Dennick, 2014). Vygotsky has defined the zone of proximal development as the gap between unassisted problem solving ability or unaided cognition, and what can be acknowledged and achieved under teacher supervision and guidance (Schunk, 2012; Dennick, 2014). According to Vygotsky, scaffolding is essentially dependent on the social interaction and engagement of learners in their society and shared cultural elements (Dennick, 2014). Therefore, Vygotsky has stated that understanding and learning are not constructed only by individuals, but by interaction and communication with a group, society, and culture (Prawat, 1999; Dennick, 2014; Akpan et al., 2020). Moreover, the main focus of social constructivism theory is interaction and collaboration in group work for successful learning. Constructivism proposes that students should not focus on memorising individual facts, but instead must develop their own definitions, meanings, and understanding through action and discovery on the basis of their experience from actions or exploration (Akpan et al., 2020).

Vygotsky proposed that language and culture play major roles in how individuals perceive the world around them, and that a group of people is necessary to construct language and conversation (Akpan et al., 2020). Social constructivism theory therefore defines knowledge as what an individual or student does when collaborating with other students or a teacher.

The use of conversation and interaction with other people is the social aspect of learning that is explained by social constructivism theory, in which this social interaction is an essential part of learning to achieve learning objectives and understanding (Akpan et al., 2020).

The social construction of knowledge can be achieved in various ways and places, through teamwork, group discussion or instructional educational learning activities (Kapur, 2018). Social constructivism is implied in education when students interact with a group of people to gain understanding and experience that will enable successful performance in tasks (Akpan et al., 2020). Social constructivism can be defined as collaborative learning because it depends on student interactions, sharing, and discussion. The design of any teaching strategy should therefore be based on interactive and grouping methods.

Teaching methods or strategies can include large or small group discussions, group projects, or group learning activities, in which students can interact with each other to complete the required assignments or projects. According to the theory, small-group work among students allows them to share ideas and discover reasons or causes and effects, thus allowing them to answer problems, complete tasks, and create new knowledge to add to their existing knowledge and experience (Akpan et al., 2020). The social constructivism framework can be applied in the classroom in the form of brain-storming sessions, collaborative learning activities, group projects, and interactive practical sessions between teachers and students (Watson, 2001; Kalina and Powell, 2009; Akpan et al., 2020).

Here, cognitive load theory was applied to the design of a practical teaching session that is aligned with the' cognitive architecture of learners. Cognitive load theory was first developed by John Sweller in 1988 to explain the three parts of cognitive architecture (Sweller, 1988),: the memory system, the type of cognitive load imposed on the working memory, and the learning process (Young et al., 2014). The memory system consists of three major elements: the sensory memory, the working memory, and the long-term memory (Sweller, 1988; Van Merriënboer and Sweller, 2010; Young et al., 2014). The sensory memory receives information via two pathways, i.e., visual and audio information, and holds this information for less than a few seconds (Khalil et al., 2005b; Van Merriënboer and Sweller, 2010; Young et al., 2014). Some information that is received by the sensory memory will not reach the consciousness (Khalil et al., 2005b; Young et al., 2014). The information then travels to the working memory, which represents the consciousness and awareness that will process and separate the visual and the auditory information (Khalil et al., 2005b; Van Merriënboer and

Sweller, 2010; Young et al., 2014). The working memory has a limited capacity and can hold the information for only a few seconds, unless it is refreshed by rehearsal (Young et al., 2014). All information is then combined and organised into meaningful units termed ‘chunks’ (Young et al., 2014). The information processed in the working memory results in words and images that are mentally arranged into a coherent cognitive representation known as a ‘schema’ (Khalil et al., 2005b; Young et al., 2014). The schemata created then connect with relevant information or knowledge that is activated from the long-term memory (Khalil et al., 2005b, 2005a; Van Merriënboer and Sweller, 2010). The schemata are then stored in the long-term memory, that stores knowledge permanently (Khalil et al., 2005b; Van Merriënboer and Sweller, 2010; Young et al., 2014). The schemata organise multiple elements and information that are created in the working memory, and all cognitive schemata, with different degrees of complexity, are stored in the long-term memory (Young et al., 2014).

the second part of the cognitive architecture is concerned with cognitive load are exerted on the working memory. Cognitive load theory identifies three types of cognitive load in the working memory: intrinsic load (associated with the main task), extraneous load (not essential to the task), and germane load (working memory that handles the intrinsic load, which leads to learning) (Van Merriënboer and Sweller, 2010). The sum of these three elements constitutes the total cognitive load (Khalil et al., 2005b). The learning process occurs when the three types of cognitive load do not exceed the memory capacity (Khalil et al., 2005b). Therefore, cognitive load theory indicates that, to achieve effective learning and to create an effective schema, the intrinsic load and germane load should be increased, and the extraneous load should be decreased, allowing the working memory to form schemata that can be stored in the long-term memory (Young et al., 2014). Additionally, the construction of schemata can be utilised by problem-solving processes that connect new elements with previous elements stored in the long-term memory (Van Merriënboer and Sweller, 2010; Young et al., 2014). The constructed schemata are then treated as elements in the working memory to help decrease the cognitive load in related tasks (Van Merriënboer and Sweller, 2010).

Based on cognitive load theory and its association with social constructivism, individual learning is less effective than learning with a group of students or individuals when the task increases in complexity (Kirschner et al., 2009). Additionally, it has been argued that the use of collaborative learning for groups of individuals can reduce cognitive load by reducing interactivity (Kirschner et al., 2018). This is can be explained by information being divided between the learners when the cognitive load is high, providing more cognitive capacity (Kirschner et al., 2009). This is known as collective working memory (Kirschner et al., 2018). The collective working memory that is generated from the collective knowledge between individuals is larger than one single memory of an individual (Kirschner et al., 2018). Thus, collaborative learning reduces cognitive load, resulting in a scaffold process for knowledge acquisition (Kirschner et al., 2018). Collaboration between learners exchanging information or resources and working on completing a task has been shown to be successful in reducing cognitive load and promoting the scaffolding process (Kirschner et al., 2018). However, successful collaborative learning should also reduce the extraneous load by providing clear information and useful resources that increase the intrinsic and germane loads (Kirschner et al., 2018). Moreover, collective knowledge and collaborative learning depend on effective collaboration between individuals (Van den Bossche et al., 2006).

Teaching approach	Brief description
1. Ascertain prior knowledge	The teacher must determine the students' background, e.g., through using good questioning skills at the start of the teaching session or verifying the pre-requisite qualifications for the course.
2. Activate prior knowledge	The teacher activates the students' prior knowledge, which they may forget or be unaware of at the beginning of a teaching session. This activation can be accomplished by reviewing prior work or asking relevant questions to bring the information to the surface.
3. Construct on existing knowledge	New knowledge can be facilitated only by existing knowledge. Thus, explaining new information by using the knowledge that students already have is important.
4. Challenge existing knowledge and misconceptions	Powerful learning happens when students are in a state of uncertainty, which can lead to cognitive conflict and the desire to resolve the conflict to achieve a sense of mental equilibrium. Teachers should structure learning situations that are challenged by evidence and demonstrations. Students should be given problem-based learning that forces them to question, abandon, or improve their existing understanding.
5. Enable the social construction of meaning	The work of Vygotsky and Piaget stresses the importance of the social nature of learning. Through social collaboration and the use of language, learners can develop cognitive skills. Vygotsky has argued that collective memory is a characteristic of individual psychology. Giving oral tasks to the students to prompt them to use new terminology.
6. Stress the context and the situation	Learning is a process of interactions among individuals, other people, and the environment. The importance of the learning

	must be indicated, and teachers must model appropriate behaviour.
7. Encourage meta-cognition	A task known as metacognition involves the construction of understanding, as assisted by reflecting on the process of learning itself. Therefore, everyone has individual ways of thinking, seeing or understanding. Moreover, on the basis of individual background, everyone has a different way of examining the world and constructing meaning within their respective context. Therefore, students should be aware of these epistemological frameworks.
8. Using active-learning techniques	The stimulation of prior knowledge by questions, the creation of cognitive dissonance and its resolution by investigation, group work, social interaction, and discussion are all active learning techniques. Constructivist theory suggests that learning should occur through doing, applying knowledge, and problem solving to be effective.
9. Enable learners to take responsibility for their learning	Because learners are at the heart of the learning process, they should know that they are responsible for their learning. Successful learning includes personal construction, and learners must take accountability for this fundamental process.

Table 2.1: Summary of the constructivist theory framework in education, as described by Dr. Reg Dennick (Dennick, 2012, 2014).

Additionally, David Kolb has made major contributions to constructivism theory. In 1982, Kolb developed experiential learning theory (ELT), which is categorised as a cognitive constructivist theory generally within cognitivism. Constructivism is a general theory regarding learning, and ELT delineates the steps and mechanisms of how learning occurs. Kolb's ELT originated from the work of three previous models and the ideas of Dewey, Lewin, and Piaget (Dewey, 1938; Lewin, 1942; Piaget, 1970). Their shared characteristics led to ELT, which Kolb claims to be a general model for learning (Kolb, 1984). ELT tends to be a learning process that merges perception, cognition, experience, and behaviour in creating knowledge (McCarthy, 2010). Kolb has explained how individual experience can be transferred to skills, attitude, and knowledge (Dennick, 2014). Kolb's constructivist ELT (KELT) explains a cycle of learning in which the learner's knowledge is converted, via activities of observation and reflection, from initial concrete experiences to conceptual concepts that can be tested in new situations. The results of these activities are new experiences and knowledge, both of which can be transformed as the cycle continues (Kolb, 1984). This cycle is called the experiential learning cycle (Kolb, 1984; Dennick, 2014).

The cycle design started from the interpretation of Lewin's model involving a feedback loop of the learning process of concrete experiences, followed by knowledge transformation through observation and reflection, thus leading to mental concepts that can be tested in new situations (Kolb, 1984). Kolb has defined the process of learning in a cycle, on the basis of Lewin's work on action research. These learning modes are transformed by the cognitive transaction initially described by Piaget. Kolb's experiential learning cycle (KELC) starts with a concrete experience, which is part of the direct experience that learners obtain from the learning process as well as old experiences (Dennick, 2014). Concrete experience is considered the origin of the cycle. The second step in the cycle is reflection and observation, in which learners start to observe new information and reflect on their knowledge or experience. The third step is abstract conceptualisation, in which the observation and reflection step leads learners either to construct new ideas or to adapt existing ideas. The final stage is active experimentation, in which the new or renewed information or knowledge is tested to determine whether it matches reality. The final step leads to a new concrete experience that starts a new cycle in a lifelong process (Kolb, 1984; Dennick, 2014). Kolb has also described that abstract conceptualisation is another resource for inner experience, and that concrete experience is not considered to be the only source of experience. An effective learning process should integrate the four steps, as Kolb explains, such that learners continually move among the four steps, such as from concrete experience to abstract conceptualisation, or from active experimentation to reflection observation (Kolb, 1984). Kolb has suggested that learners should apply the four stages equally for maximum learning, and that none of the stages should be neglected or dominant (Kolb, 1984).

Moreover, Kolb suggests that learners can be categorised based on their preference for each step in the KELC in his learning styles inventory (Kolb, 1984). The learning styles inventory identifies four learning styles that includes: “assimilative, divergent, accommodative, and convergent” (Dennick, 2014). The broad notion of learning styles proposed by Kolb has been widely criticised and discredited (Coffield et al., 2004). Thus, the learning preference is context dependent and related to the skill or knowledge being learned.

2.2 Conceptual Framework

On the basis of the theoretical foundation outlined above (**Section 2.1**), this project involved the design of learning resources using digital and 3D technologies as a conceptual and practical framework integrating and highlighting the key features of those theories.

In designing the learning activities, we considered that students or learners are at the centre of the learning process, and used designs based on learner-centred methods rather than teacher-centred methods (Ausubel, 2012; Dennick, 2014; Akpan et al., 2020). Digital and 3D learning resources can provide an effective structure for enhancing human anatomical learning and clinical imaging interpretation (Ben Awadh et al., 2022). In designing digital and 3D resource learning activities, we expected that students would originally experience and achieve ground knowledge in 3D anatomy before being shown gross anatomy structures in cross-sectional images. On the basis of the constructivist framework (Dalgarno, 2002; Ausubel, 2012; Dennick, 2014), students were expected to cognitively create an understanding of different anatomical features in terms of appearance, position, and size in the cross-sectional images on the basis of their existing knowledge and experiences regarding the same structures and relationships in 3D. Therefore, the integration of the digital and 3D resources with the 2D cross-sectional images in the learning activities was expected to enhance and accelerate the learning process by providing students with resources supporting their observations, thus enabling cognitive access to their prior 3D knowledge and understanding of the anatomical structures (Keenan and Powell, 2020). Some teachers prefer to introduce the most challenging subjects in the final stages of curricula. Ensuring that students understand basic important and general topics or concepts early in their anatomical learning is important to enhance their long-term learning. In learning activity design, preparation is provided to create an initial foundation of knowledge and experiences allowing students to build on their learning and understanding through their education, as previously described (Ausubel, 2012; Dennick, 2014).

Digital and 3D learning resources can provide a framework for students to enhance collaborative and social learning when delivered in practical sessions in the DR in the form of groups; therefore, this learning is underpinned by social constructivism (Vygotsky and Cole, 1978). In group work, students can work together to share ideas and find answers to their questions and problems, thus providing the students with new information or confirming and adding new information to their existing knowledge (Akpan et al., 2020). This approach encourages active interaction among students and teachers or demonstrators.

KELT was incorporated in the design of the digital and 3D resource learning activities. The introduction of the digital and 3D resource learning activities occurred in a practical session and initially started with the presentation of basic information regarding clinical image orientation and location and some anatomical details of the thorax with reference to the digital resources and 3D printed models. This introduction started the reflective observation stage, as described within KELC. Importantly, students can enter the KELC at any stage (Kolb, 1984; McCarthy, 2010; Dennick, 2014). The reflective observation stage allows students to transform their prior knowledge of clinical images and the anatomical structures of the thorax into a more detailed understanding described by Kolb as abstract conceptualisation. The next step involves the transformation of the newly constructed information into students' concrete experiences by providing students with an opportunity to complete tasks in handouts and to discuss and respond to questions asked by the demonstrator. These tasks rely on the use of digital and 3D resources and cadaveric materials to apply knowledge in identifying positions and anatomical structures in cross-sectional images. The KELC starts again when students repeat the reflective observation step by reviewing the teaching material on the thorax and the cross-sectional clinical images.

The digital and 3D resource learning activities can proceed in related practical sessions, with each step of the KELC involving an activity in a session (**Figure 2.1**).

Digital and 3D resource learning activities may be effective over time, because Kolb has stated that learning, development, and performance are processes of learner adaptation that differ in time scale (Kolb, 1984).

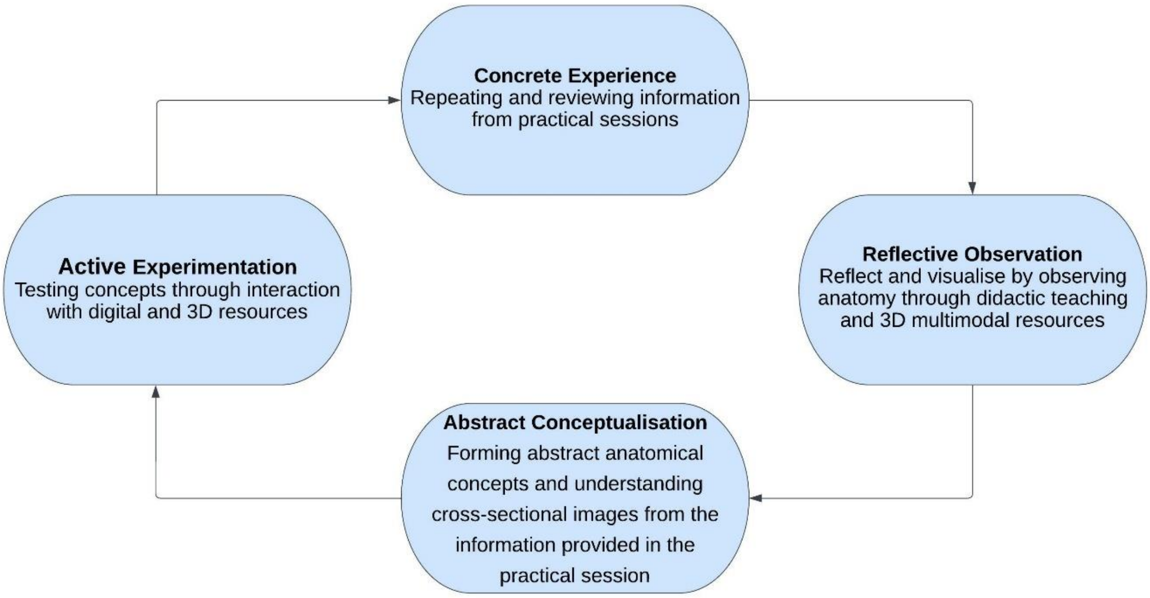


Figure 2.1: Digital and 3D resource learning activities align with KELC and social constructivism.

Digital and 3D resource learning activities are a step-by-step cyclical learning method based on constructivism, experiential learning theories (Kolb, 1984; Ausubel, 2012; Dennick, 2014), and social constructivism (Vygotsky and Cole, 1978) to enhance students' learning of anatomy.

Chapter 3. Study Goals

3.1 Study Aim

To design and evaluate 3D digital learning approaches to support students learning challenging areas of gross anatomy, embryology, and clinical-image interpretation that can be implemented into curricula to enhance student experience and understanding of these topics.

3.2 Research Questions

1. Which concepts and processes in gross anatomy, embryology, and clinical imaging do medical students find most challenging to learn?
2. To what extent do specific 3D and digital approaches enhance student experience and understanding of challenging areas of gross anatomy, embryology, and clinical-imaging interpretation?
3. How do specific digital and 3D approaches enhance the learning of challenging areas of gross anatomy, embryology, and clinical imaging?

3.3 Definitions

The definitions **(Table 3.1)** and operational definitions **(Table 3.2)** of important terms used in the research questions and in this project are outlined below.

Term	Definition
Medical Students	Year 1 and Year 2 medical students at Newcastle University, Accelerated Medical, and Physician Associates.
Clinical-imaging Interpretation	The ability to recognise anatomical features in cross-sectional clinical images, e.g., CT or MRI scans or Virtual Human Dissector (VHD) image.
Challenging Areas	Topics of learning considered to be particularly demanding by medical students.
Gross Anatomy	The branch of anatomy that deals with the structure of tissues and organs.
Embryology	The study of human development.

Table 3.1: Definitions used in the study research questions
Terms used in the research questions that needed to be described prior to the research.

Term	Definition
Concepts	Topics of learning such as understanding anatomical positions and 3D arrangement.
Processes	The learning of a topic with certain steps such as morphological changes during development.
3D Approaches	The use of physical 3D resources, such as 3DP models (**Section 5.6**).
Digital Approaches	The use of digital resources, such as interactive screens (**Section 5.6**).
Student Experience	The students' perceptions of the resources used in the study, based on responses to the questionnaire items, as described in the Methods chapter (**Section 5.6.7, 5.6.8**).

Table 3.2: Operational definitions used in the study research questions
Terms used in the research questions that have been described operationally based on the research outcomes.

3.4 Hypotheses

In this project, the blending of several teaching resources including physical and 3D digital model resources with 2D slices is proposed as a means to enhance learning and improve interpretation of anatomy structures on cross-sectional images. Furthermore, it is hypothesised that using the Sectra visualisation table (Sectra) to provide digital 3D models and 2D slices with the use of 3DP models in practical sessions can provide a framework informed by social learning theory (Vygotsky and Cole, 1978; Akpan et al., 2020), in which small groups of students can collaboratively interact with these resources during practical learning activities. In addition, it is proposed in this project and based on previous work (Vuchkova et al., 2011) that the implementation of 3D visualisation resources can support medical students and enhance their interpretation skills and ability to identify anatomical structures in clinical cross-sectional images. It is hypothesised that this can be achieved by students constructing new knowledge based on their understanding of 3D anatomy, which is underpinned by constructivist theory (Ausubel, 2012; Dennick, 2014, 2016). The introduction of remote digital learning resources as a means of self-directed learning would increase students' confidence in, and understanding of, complex or theoretically difficult topics (Morgulis et al., 2012; Keenan and ben Awadh, 2019a; Ben Awadh et al., 2022). Digital resources for the study of embryology would be expected to play a major role in improving student understanding of challenging embryology topics (Sharpe, 2003) owing to the 3D and dynamic nature of the discipline. Additionally, students can expect to have deeper insight with the implementation of these new resources during learning activities (Petersson et al., 2009; Jamil et al., 2019).

Chapter 4. Literature Review

Rationale

Performing literature reviews is an important part of research that helps establish a theoretical research framework and identify terms, methods, and policies relevant to a given topic (Cohen et al., 2018d). Three major types of literature investigation are used: literature research, literature review (narrative review), and systematic review (O'Gorman et al., 2013). Simple literature research can be rapidly performed to answer a specific question or to obtain a brief overview of a subject or a topic (O'Gorman et al., 2013).

Identifying the presence and nature of any gaps in the available literature is a key feature of a narrative literature review. The outcomes from such a review enable the gaps to be addressed in subsequent research (Cohen et al., 2018b). Here, a narrative literature review was implemented to summarise the few available studies that have investigated the anatomy education topics that students and educators consider most challenging, thus revealing the extent of further research required in this area.

Systematic reviews have been increasingly used in medicine and education in the past two decades (Moher et al., 2009; Cohen et al., 2018b). The main purpose of a systematic review is to verify and evaluate all available research, with the aim of addressing specific research questions (Glasziou et al., 2001; O'Gorman et al., 2013). A systematic review also synthesises the evidence generated by articles and studies in a particular field, while addressing the methodological rigour and the validity of the research findings (Gough et al., 2017). A systematic review process was therefore chosen for this study to identify the key literature within the broad area of technology-enhanced digital visualisation for the teaching of gross anatomy, clinical imaging, and embryology.

The systematic review process is consistent with a post-positivist or pragmatic theoretical stance, whereas narrative reviews can be considered to follow a pragmatic theoretical stance (Bearman et al., 2012; Cohen et al., 2018b). These review approaches therefore align with the epistemological perspective of the research described and reported in this thesis.

4.1 Narrative Review: Challenging Topics in Anatomy Learning

A key concern among health science educators and medical education communities relates to a potential decline in anatomical knowledge among medical and science graduates because of changes in the teaching of anatomy (Bergman et al., 2014; Fillmore et al., 2016). To ensure effective patient care and safety, learners studying medical and healthcare sciences must have a detailed and comprehensive understanding of anatomy (Javaid et al., 2018). However, according to the experiences of anatomy instructors, certain topics and subjects in gross anatomy and embryology are considered particularly demanding or problematic for students to learn, including neuroanatomy, the perineum, and the omentum (Kramer and Soley, 2002). In the literature, no specific evidence has been identified that supports the difficult nature of the most challenging topics in the disciplines of gross anatomy and embryology (Kramer and Soley, 2002). Several attempts have been made to identify demanding topics in anatomy among undergraduate students (Kramer and Soley, 2002; Hall et al., 2018; Javaid et al., 2018; Cheung et al., 2021).

4.1.1 Visualisation of 3D anatomy

To be retained, the content taught must be understood and visualised by students (Kramer and Soley, 2002). In one study, medical students at the University of the Witwatersrand (South Africa), taking an anatomy course taught through lecture-based approaches and practical sessions, spent approximately 350 hours of the course total of 460 hours on gross anatomy. The course also involved histology and embryology teaching. For their core anatomy learning, students dissected an entire human body. They were also provided with supplementary resources (prosected and plastinated specimens, radiograph images and scans, a histology microscopic practical, computers, and videos). The authors administered a questionnaire to second-year medical students (n = 259), but a relatively low response rate was achieved (34%, n = 88) (Kramer and Soley, 2002). The questionnaire was designed to gain information but not to provide any new facts. Students completed the questionnaire at the end of the academic year to ensure that teaching in all topics in anatomy, embryology, and histology had been delivered. Analysis of the data showed that 90% of the student respondents found that the pelvis, neuroanatomy, the perineum, the omentum, and body cavities were the most challenging topics, for several reasons, including I) the students experienced challenges in forming 3D representations of specific anatomical structures; II) the area was difficult to visualise or view; III) the area was either difficult to access or damaged during dissection, and the students were not able to go back for revision; and IV) the volume of content, level of detail, and complexity of structures were problematic. Histology was ranked as troublesome topic, mainly because of the difficulty of the concepts and the delivery of poorly structured lectures that would have benefitted from more visual aids, such as 3D models and diagrams. Insufficient time, particularly for the practical sessions, was another reason for the difficulty in learning histology.

Embryology was identified as a difficult topic because the respondents reported an inability to visualise, understand, and comprehend its sequences and developmental processes (Kramer and Soley, 2002). Specifically, 35% of respondents (n = 31) found that details of the 3D dynamic processes associated with the development of the body cavities and mesenteries were difficult to visualise because the available teaching and study resources were 2D (lectures and videos).

Indeed, the key finding of this study was associated with challenges in 3D observation, 3D conceptualisation, and 3D visualisation experienced by students. Additionally, students reported difficulties in successfully identifying the orientation of observed structures and in recalling the structures of 3D features after being presented with 2D images. The use of more visual aids, such as 3D resources, videos, and computers, was suggested by the students to improve the learning of gross anatomy, embryology, and histology. The authors proposed that students would benefit from increased time on tasks, practical sessions, and dissection, as well as more lectures and resources, to aid in the learning of challenging topics in anatomy. The authors recommended that students should be taught to depend more on mental imagery in anatomy learning, and that visual imagery, involving spatial understanding of location, size, orientation, and scale, should be introduced by anatomy teachers to their students as an important mode of anatomy learning (Kramer and Soley, 2002).

4.1.2 Neuroanatomy and neurophobia

Neuroanatomy has been identified as a particularly challenging area of anatomy learning (McCarron et al., 2014). For example, some dental students experience difficulties in locating the inferior alveolar nerve block because of a lack of neuroanatomy knowledge (AlHindi et al., 2016). In an earlier study, second-year medical students had difficulties in retaining neuroanatomical information (D'Eon, 2006), thus emphasising why neuroanatomy is a difficult topic. Additional studies have shown that the fear of neuroanatomy among clinicians can increase with a lack of neuroanatomy knowledge and understanding (Jozefowicz, 1994;

Fantaneanu et al., 2014; McCarron et al., 2014; Pakpoor et al., 2014; Abushouk and Duc, 2016).

The reasons why neuroanatomy is a challenging topic remain under investigation and have not been fully explained (Javaid et al., 2018). One study has examined students (n = 383) in different programs (undergraduate medicine, graduate medicine, dentistry, occupational therapy, and speech and language science students) who attended 18 hours of lectures with four long prosection tutorials in their neuroanatomy education and were taught the same overall neuroanatomy content. A survey was administered to all participating students, and the data analysis indicated that neuroanatomy was the most challenging area in both systems- and region-based anatomy teaching. Further thematic analysis revealed three major themes: the complexity of the topic, breadth of the curricular content, and difficulty in visualisation of neuroanatomical structures (Javaid et al., 2018). Most students (81.8%) in the study indicated that their neuroanatomy learning was enhanced by the use of computers. Newer resources, such as computer and web resources, are more important for enhancing learning than traditional resources, such as lectures and notes. Many factors have been identified that make neuroanatomy and other topics challenging (Javaid et al., 2018) (**Table 4.1**).

1	Topic complexity
2	Understating of clinical aspects
3	Memorisation of terminology
4	Visualisation of anatomical structures
5	3D relationships among anatomical structures
6	Volume of content to learn in a short period of time

Table 4.1: Factors making neuroanatomy a challenging topic to learn

Limited dissection time, short practical sessions, a large volume of content, limited lecture time, and poor resources are all factors making the learning of neuroanatomy and anatomy difficult (Javaid et al., 2018).

Questionnaires such as that conducted by (Hall et al., 2018) have identified the challenging anatomy topics for medical students and the factors underlying these challenges. The authors administered a questionnaire to second year medical students (n = 185) and 91 competitors at the 2015 National Undergraduate Neuroanatomy Competition (NUNC) to determine their perceptions. The NUNC competition was a one-day event in which all medical students from the United Kingdom and the Republic of Ireland are eligible to voluntarily participate. More than half the second-year medical students and a small number of the NUNC attendees provided feedback indicating that neuroanatomy was the most difficult subject. Further analysis indicated that the pelvis and the head and neck were considered challenging topics in anatomy. Second-year medical students (n = 87) and NUNC participants (n = 26) stated that the reasons why neuroanatomy was challenging were the volume and the details of the content material given to them. New methods and resources should be directed to students where they need it most to gain the maximum benefits.

4.1.3 Anatomy content

The difficulties experienced by students learning anatomy can be due to the content itself. In one study, students did not find anatomy to be a stimulating or engaging subject, potentially leading to inadequate anatomy learning (Bergman et al., 2013). Student perceptions that anatomy learning should be based primarily on memorisation may also affect their engagement and learning (Miller et al., 2002). Moreover, content overload makes anatomy a difficult subject to learn (Wright, 2012). In a study by Lieu and colleagues at the University of California (Irvine) in the United States, participating students (n = 198) attended a total of 25 hours of lectures and 30 hours of laboratory training in a systems-based anatomy course (Lieu et al., 2018). The participating students majored in biological sciences, nursing sciences, and pharmaceutical sciences. At the end of the course, students were asked to rate the most and least challenging body systems, and 60% of the students indicated that the nervous system is the most complex system, followed by the muscular system (13.1%). The study also reported that the least challenging system was the cardiovascular system. Students reported that the nervous system was the most challenging topic to study because visualisation of the nervous systems structures is difficult (Lieu et al., 2018). The muscular system is difficult to learn because of the large number of muscles that students must learn. However, the cardiovascular and skeletal systems were considered the least challenging because the students had access to models enabling easy visualisation. Furthermore, the key anatomical concepts and features that are typically studied within these systems are likely to be less complex than those found in the nervous system (Lieu et al., 2018).

Anatomy is an important subject in the medical curriculum that provides future physicians and clinicians with the anatomical knowledge needed to diagnose and safely treat patients in practice (Turney, 2007). A decrease in anatomy teaching time has been found to result in inadequate anatomical knowledge for students that might result in unsafe medical practice (Singh et al., 2015). Four groups (second-year medical students (n = 11), sixth-year medical students (n = 6), junior physicians (n = 4), and anatomy educators (n = 8)) participated in the research by (Cheung et al., 2021), which aimed to identify the most challenging anatomical regions to study. To determine the participants' perceptions, interviews were conducted, and the data were analysed with respect to the academic background of the participants. Analysis of transcripts from face-to-face semi-structured interviews indicated that neuroanatomy and the head and neck were considered the most challenging regions by all four groups (Cheung et al., 2021). The first aim of the study was to analyse the students perceptions of the challenging topics by counting the participants' responses and then determning the percentage distribution of the response among the four participating groups (Cheung et al., 2021). Further analysis indicated that the nerves and blood vessels were considered troublesome to all groups, particularly second-year medical students. Moreover, the pelvis, perineum, abdomen, and gastrointestinal system were also identified as challenging topics. The thorax and musculoskeletal systems were identified by the four learner groups as the least challenging regions or systems.

Three major themes arose from the analysis of interview data with respect to anatomy learning challenges are shown in **Table 4.2.**

1	Visualisation of the body structures
2	Overload of the information
3	Curriculum design issues

Table 4.2: Themes arising from the analysis of interview data
Three major themes arose from the analysis of interview data explaining the challenges faced in learning anatomy (Cheung et al., 2021).

Participants considered the structures that can easily be seen, such as the heart, to be less challenging than other structures that are difficult to observe or visualise through mental images, such as the nerves. Students stated that the ability to mentally visualise anatomical structures is an important factor in learning anatomy (Pandey and Zimitat, 2007). The differences in student experiences and skills resulted in diverse responses regarding the challenging topics in anatomy. This finding will allow educators to design effective curricula and use appropriate evidence-based resources in teaching.

The aim of the research here was to build on previous studies (Kramer and Soley, 2002; Hall et al., 2018; Javaid et al., 2018; Cheung et al., 2021) to generate deeper insights into the perceptions of health profession students regarding the challenges of learning the anatomy of all regions throughout their undergraduate anatomy curricula.

Another aim of this research was to investigate the factors that make anatomy learning difficult for medical students. A major limitation of the previous studies reviewed above, with one exception (Cheung et al., 2021), is that no attempts were made to use interpretivist studies incorporating focus groups or interviews to generate qualitative data for the purposes of exploring student perspectives of challenges in anatomy learning.

Given the extensive limitations in both the quantity and quality of available published literature with respect to the most challenging topics in anatomy learning, and due to the context-specific nature of education and learning, it is important to address gaps in the literature by generating valuable insights and findings within our own context regarding the challenging topics, areas, and regions in anatomy learning, with a view to developing effective and transferable approaches for addressing these elements

4.2 Systematic Review: Digital Medical Imaging Resources

4.2.1 Introduction

Traditional anatomy teaching methods commonly include lectures, clinical cases, dissection, prosection, and self-directed learning resources using multimodal resources and 2D images (Murgitroyd et al., 2015). Anatomy is a discipline that can be considered a visual science, wherein understanding and visualisation of structure, function, and relationships is required (Tan et al., 2012). Because the anatomical structures are 3D, students may experience difficulty in using their spatial abilities to connect different anatomical structures (Keenan and ben Awadh, 2019a; Ben Awadh et al., 2022). Students who have difficulties in visualisation or mental rotation (MR) of different anatomical structures to transform 2D images into 3D structures may experience challenges (Marsh et al., 2008; Brewer et al., 2012). Using 2D resources such as MRI scans is likely to impose a high cognitive load on students performing mental reconstruction (Duncan and Ayache, 2000). Poor retention of anatomical knowledge among first-year medical students can limit their long-term understanding of the topic (Klement et al., 2011; Ward, 2011). Therefore, anatomy educators must combine multiple resources when teaching anatomy to achieve the best possible benefit to student learning, such as plastic models, dissection, and new learning software (Estai and Bunt, 2016; Keenan and Powell, 2020). Students can effectively see 3D views of anatomical structures through dissection, thus improving their perception of the locations and relationships among anatomical structures, in support of the knowledge obtained from lectures and practical sessions (Rizzolo and Stewart, 2006).

Previous research has indicated that implementing new technology-enhanced learning and teaching (TELT) resources in curricula can effectively provide new tools, thereby increasing student engagement and consequently understanding and knowledge gain (Garrison and Akyol, 2009). A growing body of literature demonstrates that radiology training is crucial for clinical diagnosis as well as patient treatment and management (Mirsadraee et al., 2012). Radiology education is an important part of anatomy coursework (Vuchkova et al., 2011; Keenan and Powell, 2020). Clinical imaging interpretation and understanding of the pathologies shown in radiographic images requires a high level of anatomical knowledge and understanding (Miles, 2005; Murphy et al., 2015; Heptonstall et al., 2016).

Medical students must have a basic understanding of radiology and clinical imaging regardless of their future specialty (Webb and Choi, 2014). Additional radiology training can support anatomical learning and 3D/2D understanding (Keenan and ben Awadh, 2019a; Keenan and Powell, 2020), and it is likely to be used by all students in clinical practice at some point (Wu et al., 2012).

Many researchers have suggested that radiology education should be integrated within existing programs of anatomy education (Miles, 2005; Kourdioukova et al., 2011; Keenan and ben Awadh, 2019a; Keenan and Powell, 2020; Ben Awadh et al., 2022). The development of radiology teaching and curriculum frameworks with clear learning objectives and outcomes has become essential (Webb et al., 2013). The use of clinical and radiological imaging is changing how medical education is delivered by using advanced technologies and resources to improve the interpretation of human body structures (Miles, 2005; Tam, 2010; Phillips et al., 2013b). The visual nature of clinical imaging makes the new TELT resources useful in delivering radiology education for students (Grunewald et al., 2003; Miles, 2005; Ketelsen et al., 2007).

Introducing students to radiology education in their early years advances their interest in radiology and improves their perception of radiology and its applications in anatomy learning (Branstetter IV et al., 2007; Lee et al., 2007; Phillips et al., 2013b). Interpretation and understanding of the 3D aspects of clinical images, such as MRI and CT scans, is an issue in all medical professions (Preece et al., 2013). Medical students must crucially understand the 3D aspects of human anatomy in clinical images. Because of a lack of resources, students usually depend on textbooks and lectures, which provide only 2D representations of the human anatomy, thus decreasing knowledge retention (Preece et al., 2013).

Regardless of their healthcare discipline, without adequate anatomical knowledge and understanding, clinical professionals cannot perform effective diagnoses, because extensive understanding and knowledge of the exact locations of viscera and tissues is required (Singh et al., 2015). The benefits of TELT in radiology learning and teaching have become important, especially with the COVID-19 pandemic (Evans et al., 2020), and have increased interest in radiology education and the development of computer-based resources for radiology education (Marker et al., 2010; Tam, 2010).

Previous evidence has suggested that 3D computer models provide many benefits when access to cadavers is limited, and they are also important for spatial understanding and student interaction (Tan et al., 2012). VTs produced by manufacturers including Anatomage (Anatomage Inc., San Jose, CA) and Sectra (Sectra AB, Linköping, Sweden) are recently introduced technologies that are used to teach anatomy (Keenan and ben Awadh, 2019a; Ben Awadh et al., 2022). The Sectra VT (Sectra) uses large interactive screens with an image display system that allows interaction and communication with 3D human body images and CT or MRI scans. This screen allows students to interact with and manipulate 3D human body images and CT or MRI scans to gain better understanding of the 3D aspects of the human body. Sectra VT allows students to interact with virtual images and representations of real-life bodies based on clinical imaging (Keenan and ben Awadh, 2019a; Sectra, 2021a; Ben Awadh et al., 2022). Such interaction allows students to gain a deep understanding of the 3D aspects of anatomy and clinical images. Sectra provides many institutions and hospitals worldwide with real-life clinical data, some of which are obtained from real patients (Sectra, 2021a). All patient information is stored anonymously and confidentially to avoid any legal or ethical issues. Sectra uses a cloud-based system, which allows users to access clinical cases, which large consist of CT and MRI stacks, and relate them to normal anatomy, pathology, trauma, surgery, and other specialties via the SEP (SEP). Cases can be viewed and manipulated remotely within the SEP by educator and student users on their own devices or presented on the Sectra VT for practical teaching purposes. A major advantage of the Sectra network is that it allows institutions to share cases and information with other Sectra users across institutions worldwide as an example SEP (Keenan and ben Awadh, 2019a; Sectra, 2021a; Ben Awadh et al., 2022).

Several studies have investigated the effects of using 3D visualisation software to aid students' understating and learning of radiographic interpretation (Vuchkova et al., 2011). Digital visualisation technologies can be valuable for student learning (Choudhury et al., 2010; Palombi et al., 2011; Webb and Choi, 2014). Moreover, 3D visualisation can improve student understanding of anatomy (Silén et al., 2008). In recent years, the literature has increasingly reported the effectiveness of 3D resources in anatomy education and learning (Rizzolo et al., 2006; Hilbelink, 2009; McNulty et al., 2009; Chariker et al., 2011). The next section presents some studies that investigate the benefits of digital resource usage in anatomy education.

4.2.2 Systematic review: Aim and research questions

The main aim of the present systematic review was to identify the value of 3D visualisation resources for enhancing medical student experience and their understanding of anatomy and clinical-image interpretation. To accomplish this aim, the following questions were formulated:

1. How can digital and 3D approaches enhance the learning of challenging 3D concepts and processes in gross anatomy?
2. To what extent do digital medical imaging resources enhance student experiences, performance, and understanding of clinical-image interpretation?

4.2.3 Systematic review: Methods

The guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) were followed in this review to report the findings, including a flow diagram, protocol guidance, and an inclusion and exclusion checklist (Moher et al., 2009; Page et al., 2021).

Search strategy and search terms

The review aimed to identify published studies on 3D visualisation technologies, measure their benefits, and assess student experiences. An electronic search of the PubMed database was conducted. The date was restricted to between 2000 and 2021 to only include recent studies. The combinations of search terms included education type, targeted sample, and technology used, as presented in detail in **Table 4.3**.

Education type	Technology used	Targeted sample	Results
Anatomy education	(and) digital imaging resources	(and) undergraduate	17
Anatomy education	(and) digital imaging resources	(and) medical students	19
Anatomy education	(and) 3D digital	(and) undergraduate	37
Anatomy education	(and) 3D digital	(and) medical students	59
Anatomy education	(and) technology enhanced learning	(and) medical students	100
Anatomy education	(and) technology enhanced learning	(and) undergraduate	77
Anatomy education	(and) 3D visualisation	(and) undergraduate	60

Table 4.3: Keyword terms used to search for studies included in the systematic review

Inclusion and exclusion criteria for the reviewed studies

The titles and abstracts were screened for all related articles, and the full text of all included articles was reviewed. Studies on embryology and histology were excluded to focus on gross anatomy and clinical imaging. No geographical restrictions were imposed, and studies from multiple countries were included. Only studies in English were included in the systematic review, and studies in any language other than English were excluded. The studies that met the inclusion criteria that are presented in **Table 4.4** were included in the review. The database research is outlined in **Figure 4.1.**

Description	**Inclusion criteria**
Data	Database search to ensure examination of all appropriate articles available in the field
Language	Inclusion of only studies in the English language in the systematic review; exclusion of studies in any language other than English
Study type	Inclusion of only peer-reviewed research studies examining the 3D visualisation resources used to teach anatomy and radiology
Participants	Inclusion of students in medical and health professions (e.g., nursing, physical therapy, etc.)
Student learning and experience	Demonstration of the extent to which digital medical imaging resources enhance medical student experience and understanding of anatomy and clinical image interpretation
Defining quality	Inclusion of all validated results perceived by students and experimental data; assurance that the reviewed studies focused on students in medicine and medical professions; presentation of data analysis and results from the various methods used (experimental testing, Likert-type and free-text questionnaires, or focus groups)

Table 4.4: Description of the inclusion criteria applied in this systematic review

Process of article selection and data extraction from the selected studies

The database research outlined in **Figure 4.1** was used to identify the studies. All selected studies were then reviewed according to the defined inclusion criteria (**Table 4.4**)**.** The main data extracted from the selected studies were the title, authors, year of publication, subject area (anatomy), population type and number (medical and allied health undergraduate students), country and university where the study was conducted, method of evaluation (questionnaire, pre-testing/post-testing, or focus group), study aim, and main results/conclusions. The selected studies were then placed in **Table 4.5**, and the inclusion criteria were applied independently.

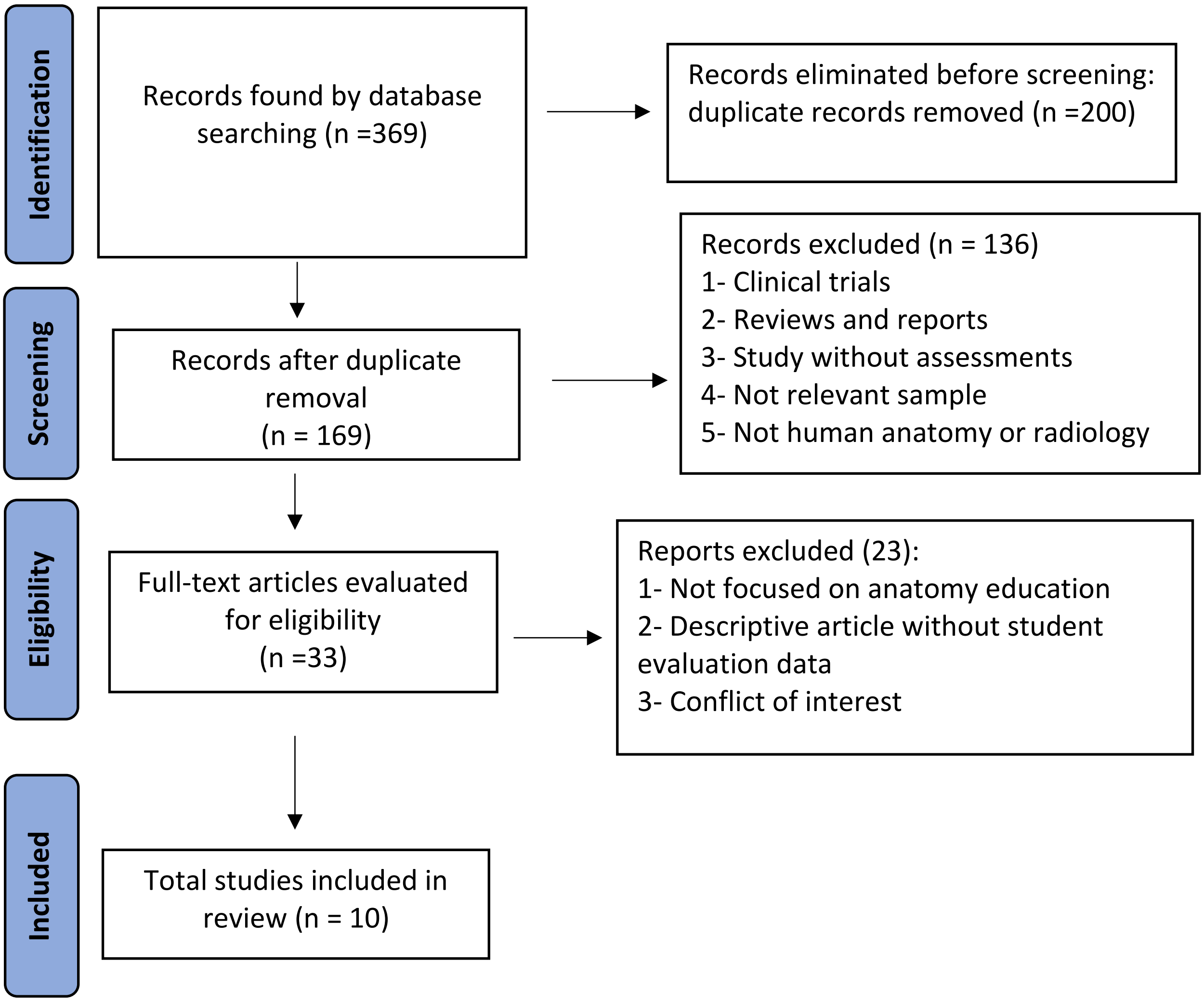


Figure 4.1: Summary of the selection process for studies included in this review
The figure shows the process presented in the form of a PRISMA flow diagram (Moher et al., 2009).

Number	Reference	Title	Targeted sample	Study location	Methods	Study focus	Analysis and findings
1	(Silén et al., 2008)	Advanced 3D visualization in student-centred medical education	Medical students- (n = 62) Physiotherapy (n = 17)	Linkoping University, Sweden	Questionnaire (Likert-type)	Introducing new 3D datasets in the curriculum to enhance the educational value of the 3D visualisation in anatomy and physiology learning	Students are stimulated by the introduction of 3D images and films to improve understanding and obtain more insight into the different sizes and shapes of organs in relation to other structures. Virtual dissection provides students with more options than regular dissection, such as the ability to interact with and rotate anatomical structures.
2	(Petersson et al., 2009)	Web-based interactive 3D visualization as a tool for improved anatomy learning	Second and fifth semester medical students (n = 75)	Linkoping University, Sweden	Questionnaire (Likert-type) Knowledge assessment test	Determining the benefits of 3D visualisation as a learning tool Investigate the value of using 3D visualisation to meet anatomical learning objectives	Student perceptions were positive regarding the EVA program (an interactive online tool) compared with a textbook but not dissection. Significant improvements in the knowledge test showed potential benefits in anatomy learning for students.

3	(Turmezei et al., 2009)	A survey of medical students on the impact of a new digital imaging library in the dissection room	First year medical students (n = 141)	University of Nottingham, United Kingdom	Questionnaire (five-point Likert-type)	Investigating student perceptions regarding digital image library adjustment in dissection sessions	The use of a new digital image library helped students understand the relevant anatomy. The digital library can be used for clinical practice in the future. The digital library was user friendly for students.
4	(Beerman n et al., 2010)	3D visualisation improves understanding of surgical liver anatomy	Fourth- and fifth-year medical students (n = 160)	University of Heidelberg, Germany	Questionnaire (five-point Likert-type) Knowledge test	Examining whether 3D representations can improve students' anatomy education, such as that of liver anatomy, and whether men benefit more than women from 3D presentation	The 3D presentation modality improved student performance. Men performed better than women with the use of 3D presentation.
5	(Vuchkova et al., 2011)	Testing the educational potential of 3D visualization software in oral radiographic interpretation	Fourth-year dental students (n = 59)	University of Queensland, Australia	Questionnaire (Likert-type) MR test Radiographic interpretation test	Investigating the effects of 3D visualisation software on dental students, and evaluating their learning and understanding of radiographic interpretation	Students provided positive feedback regarding how the 3D visualisation software enhanced their learning of radiographic interpretation. The quantitative data showed no significant improvement in student radiological interpretations skills.

							No relationship between student MR test scores and radiological interpretation test scores was observed, thus suggesting that MR does not affect radiological interpretation.
6	(Webb and Choi, 2014)	Interactive radiological anatomy e-learning solution for first-year medical students: development, integration, and impact on learning	First-year medical students (n = 116)	University of Southampton, United Kingdom	Questionnaire (five-point Likert-type) Focus group Pre and post test	Investigate student performance and experience in using RA eLearning.	RA eLearning enhanced anatomy and radiology learning for students. Student interest in radiology increased through their experience with RA eLearning. RA eLearning can help students view many examples of clinically relevant anatomy. A learning environment can be created through a well-designed TELT solution, as an effective method in teaching anatomy and radiology.
7	(Ruisoto Palomera et al., 2014)	Enhancing neuroanatomy education using computer-based instructional	Volunteer students enrolled in a medical undergraduate	University of Salamanca, Spain	Questionnaire (Seven-point Likert-type) Surface development test	Developing a 3D image tool to teach neuroanatomy Determining whether students' visuospatial	This approach is effective in achieving good understanding of complex neuroanatomical concepts.

		material	anatomy course (n = 65)		to measure visuospatial ability	ability affects educational value	The use of 3D models will reduce the cognitive load associated with the mental reconstructions of different anatomical structures. Students are provided with self-directed learning resources, thus increasing their engagement. No significant difference was observed between students with high and low levels of spatial ability regarding the educational value of this tool.
8	(Moro et al., 2017)	The effectiveness of virtual and augmented reality in health sciences and medical anatomy	Participants from various majors (biomedical, health sciences and medical students, n = 59)	Bond University, Australia	• Questionnaire (four-point Likert-type to rate any adverse health effects and another five-point Likert-type to obtain students' perceptions regarding the tools) 20 question anatomy test to evaluate acquired	Identifying the effectiveness of VR, AR, and 3D tablet resources and whether these resources enhance students' anatomy learning	All three modes of learning used in this study were equally effective in anatomy teaching. This study showed great promise for the effectiveness of VR and AR in supplementing traditional teaching methods in anatomy education. Most students reported that they enjoyed using

					knowledge (ten questions on anatomical knowledge and ten questions classified as spatial questions.		these three tools in learning anatomy.
9	(Maresky et al., 2019)	Virtual reality and cardiac anatomy: exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education	First-year medical students (n = 41)	University of Toronto, Canada	Questionnaire (Likert-type) Testing (five anatomy questions with five visual-spatial questions)	Testing the viability of computer-generated models for teaching cardiac anatomy	The medical students showed significant improvements after using the VR resources. Students had positive perceptions regarding the VR resources.
10	(Jamil et al., 2019)	Three-dimensional visualization software assists learning in students with diverse spatial intelligence in medical	First-year undergraduate medical students (n = 67)	Aga Khan University, Pakistan	Questionnaire (five-point Likert-type) MR test (the group attending the training session had a significant improvement in MR test results)	Evaluating the effectiveness of MR training and the use of the 3D software among medical students	This study showed the effectiveness of 3D visualisation software on anatomy learning for undergraduate medical students. Student performance significantly increased through learning via a 3D

		education			Experimental testing (two groups were tested: an MR trained group and an untrained group) Both the MR trained group and untrained group showed significant improvement		visualisation application, regardless of their MR abilities and whether they had MR training.

Table 4.5: Summary description of the ten studies included in this review (organised by date of publication)

4.2.4 Results

Overview of the studies included in this review

A total of 369 articles were identified through database research with the steps outlined in **Figure 4.1**. After the removal of duplicate studies (n = 200), a total of 169 studies were included for screening. A total of 136 studies were excluded after application of the inclusion and exclusion criteria, because some articles explained simple workflow methods; some articles did not focus on anatomy education; and some citations were systematic or literature reviews. Consequently, a total of 33 articles were considered for eligibility, and a full review was performed. Of these, 23 studies were excluded from the review because they were illustrative reports of clinical trials; the articles focused on the technology without any education evaluation; or medical and allied health students were not the targeted sample.

Thus, a total of ten articles that met the criteria were included in this review (**Figure 4.1**).

The studies were conducted primarily in the following countries: the United Kingdom (n = 2; 20%), Australia (n = 2; 20%) and Sweden (n = 2; 20%). The other studies were conducted in Germany (n = 1; 10%), Spain (n = 1; 10%), Canada (n = 1; 10%) and Pakistan (n = 1; 10%).

Further analysis was performed regarding the types of participants. Most studies examined medical students as the main sample (n = 6; 60%). One study covered the effect of 3D visualisation software use in anatomy education among dental students (n = 1, 10%). The remaining three articles covered doubled majors (two subject areas) of the participating students. Another study included all volunteer students enrolled in a medical undergraduate anatomy course. A further article sampled biomedical, health sciences, and medical students. The final article included medical students and physiotherapy students **(Table 4.5)**. Only three studies included more than 100 participants (30%), and the other studies included fewer than 100 participants (n = 7; 70%).

The teaching resources used in the studies included in this review were divided into digital and non-digital. The digital resources included 3D images and films, 3D visualisation resources, radiological anatomy (RA) e-Learning and VR. The non-digital resources included lecture presentation, 2D images, books, and cadaveric dissection. Importantly, studies were included that collected experimental or self-reported data, or both, because many systematic reviews would be likely to choose only one or the other.

Imaging and digital resources in anatomy education

3D images and films

New techniques to visualise dynamic movements, such as the blood flow in vessels, have been developed for therapeutic and diagnostic purposes (Silén et al., 2008). Students were introduced to different 3D images and films consisting of rotation of a CT image of the heart and an MRI film of the pumping heart (Silén et al., 2008). In the same study, students were introduced to VR. Questionnaires were administered to students to gather more information about the different interventions used in the study. Students found that the 3D images helped them with understanding of anatomy. Moreover, the students found that the lectures with the 3D images were valuable and encouraged them to participate in learning (Silén et al., 2008). The virtual dissection provided students with a clear picture, thus increasing their participation and understanding, resulting in a positive perception among students (Silén et al., 2008).

Virtual anatomy EVA-program interactivity

The use of Education Virtual Anatomy (EVA)-program interactivity as a 3D visualisation technology has been investigated by (Petersson et al., 2009). In that study, the focus was to investigate the benefits of introducing new 3D visualisation resources as a learning tool. A total of 137 students were introduced to a web-based database and viewed nine interactive 3D movies that covered most of the major arteries of the body. Student perceptions regarding the new interactive 3D movies were gathered through a questionnaire. The EVA program's interactivity with the 3D representation were identified to provide advantages over traditional methods of teaching (Petersson et al., 2009). Student perceptions were positive regarding the EVA program compared with textbooks, but not dissection and knowledge tests, and the EVA program significantly improved learning (Petersson et al., 2009).

Digital imaging library for radiology learning

Radiology and clinical imaging are considered an important part of anatomy education for undergraduate medical students; thus, the use of new resources has been proposed to support improvements in radiology understanding (Turmezei et al., 2009). In that study, two computers with monitors were placed in each teaching bay in the DR. The computer stations contained the digital imaging library, which consisted of 213 separate images or image series including normal and abnormal clinical images. Most images were radiographs, and the rest were from different modalities, such as CT, angiography, fluoroscopy, and ultrasound. An instruction sheet was given to the first-year medical students (n = 260) to access the digital imaging library during the dissection sessions. Students were encouraged by the instructors to use the digital imaging library as a self-directed learning resource. A five-point Likert-type questionnaire with free-text questions was administered at the end of the eighth dissection session to assess students' attitudes toward the use of the digital imaging library within the dissection session (Turmezei et al., 2009). The majority of students in the cohort completed and submitted the questionnaire (n = 141, 54% response rate). The authors claimed that the use of the new digital image library helped students understand the relevant anatomy. Students perceived that the digital library could be used in the future for clinical practice, and that the library interface was user-friendly and accommodating to students. However, some participants (24%) reported that the images required further labelling to support their orientation and interpretation.

Anatomy teaching and 3D presentation

(Beermann et al., 2010) examined whether 3D representation might improve students' anatomy education, such as in liver anatomy, and whether males benefit more than females from 3D presentation. To test the benefits of the 3D representation, a computer-based teaching session was developed. The participating students were randomly assigned to groups using 2D images, 3D images in one colour, or 3D images in many colours. All participating students were in their fourth or fifth year of training (n = 160). At the end of the session, students were given 11 medical questions and four evaluation questions. The test scores were significantly higher for students who used the 3D images presentation in one colour or in multiple colours than only 2D images ($P < 0.001$). The male students performed significantly better than the female students when both used the 3D modalities ($P < 0.03$). The results showed no sex differences in performance when 2D images were used (Beermann et al., 2010).

3D visualisation software to teach radiological interpretation

One study investigated the effects of 3D visualisation software on student learning and understanding of radiological interpretation of pathology (Vuchkova et al., 2011). The participating students were trained to use 3D visualisation software. The participants took a pre-test before using the 3D software and a post-test after using the 3D software. At the final stage, all participants were asked to complete a Likert-type questionnaire to gather data on their impressions of the effects of the 3D software on their education and radiological interpretation (Vuchkova et al., 2011). Findings indicated that the majority of students preferred 3D visualisation software when compared to textbooks. More importantly, most participating students had remarkably positive perceptions regarding using 3D visualisation software to enhance their learning of clinical imaging interpretation (Vuchkova et al., 2011). In the same study, no relationship was found among students' MR test scores and their radiological interpretation test scores, thus suggesting that MR does not affect radiological interpretation. The statistical analysis of the pre-test and post-test showed that student performance was not improved by the use of the 3D visualisation software (Vuchkova et al., 2011).

Radiological anatomy eLearning resources

The use of radiological anatomy (RA) eLearning resources for TELT has been applied in a previous study, in which RA eLearning was used for the identification and the description of the bones and joints of both the upper and lower extremities (Webb and Choi, 2014). A large number of X-rays were included in the RA eLearning, showing the normal and pathological anatomical structures of the upper and lower extremities that were introduced to Year 1 medical students (n = 116) (Webb and Choi, 2014). The effectiveness of the RA eLearning was evaluated through questionnaires, focus groups, and pre and post tests. The participating students were then divided into two groups: a group using RA eLearning (users) and a group that did not use RA eLearning (non-users). The test results showed no significant differences in student performance between groups; however, students had higher scores on the radiological anatomy questions than on questions not relevant to radiological anatomy. The questionnaire and focus group data showed that RA enhanced anatomy and radiology learning for students. Furthermore, the RA eLearning helped students understand the clinical relevance of anatomy and increased their interest in radiology education (Webb and Choi, 2014). RA eLearning can increase student engagement in radiology and their enjoyment in continued learning of radiology, thus positively increasing their appreciation of radiology in medical practice.

Anatomy and the development of 3D digital brain models

Development of representative 3D digital brain structure models has been performed in AMIRA software, and an anatomical and functional viewer has been created to support 3D brain structure and display sectional functional images in different planes (sagittal, axial and coronal) (Ruisoto Palomera et al., 2014). The benefits of the interactive visualisation of the brain structures and student perceptions have been investigated with a seven-point Likert-type questionnaire. 65 students participated in the study. Students had positive impressions regarding the use of 3D tools in neuroanatomy learning. Student visuospatial abilities did not affect the educational value of the 3D tools used for learning spatial relationships and image interpretation (Ruisoto Palomera et al., 2014).

VR and 3D visualisation technologies

A recent review of the literature on the effectiveness of the 3D visualisation technologies and the use of VR and AR in anatomy education have been analysed (Moro et al., 2017). A total of 59 participants were divided into three groups that received lessons on skull anatomy through the use of VR, AR, or 3D software on a tablet device. Students were asked to complete an adapted questionnaire to identify their perceptions and a 20-question anatomical test to assess improvement (Moro et al., 2017). No significant difference in test scores was observed among the three groups. The questionnaire results indicated that students preferred the new virtual tools and wanted to use them at their own pace rather than at locations or times set by the educator (Moro et al., 2017). However, some health conditions arose when using the tools. For example, some students who used the VR experienced dizziness, headaches, and discomfort (Moro et al., 2017).

Another study examined the efficacy of VR in teaching cardiac anatomy (Maresky et al., 2019). Participating medical students (n = 42) were divided into two groups: a control group that continued with independent study and an intervention group given 30 minutes of VR experience. Both groups started with a pre-test of ten questions (five cardiac anatomy questions and five visual-spatial questions). Both groups completed a post-test, and the control group was then allowed to use the same VR simulation as the intervention group. At the end of the study, a questionnaire was administered to the participating students to gather their insights regarding the effectiveness of VR as a learning tool (Maresky et al., 2019). The control group showed no significant difference between tests, whereas the intervention group showed a highly significant improvement ($P < 0.001$) between the overall pre-quiz and the post-quiz. Most of the intervention students participated in the study agreed or strongly agreed that the cardiac VR improved their anatomy learning and visual-spatial skills (Maresky et al., 2019).

3D software for anatomy education

The effectiveness of the MR training on learning outcomes among medical students and the benefits of using 3D software in teaching have been investigated (Jamil et al., 2019) in a study of 67 medical students, who were divided into an MR-trained group and a group that did not receive MR training (untrained group). A pre-MR test was given to the MR-trained group, and a post-MR test was given at the end of the training. After six weeks, a teaching session was organised for both groups (trained and untrained). Before the lecture, students from both groups took a multiple-choice pre-test. During the session, students used 3D visualisation software (Human Anatomy Atlas from Visible Body). At the end of the session, a post-test and a questionnaire were administered to students from both groups to assess their knowledge gain and their perceptions regarding the use of 3D visualisation software. Analysis of the MR test scores showed a significant increase ($P = 0.011$) in performance in the trained group between the pre-MR test and the post-MR test. Interestingly, male students scored higher than female students in MR training. In the analysis of the effectiveness of the 3D visualisation software in teaching, the trained group scored higher in both the pre-test and post-test than the untrained group, but both groups showed a similar improvement trend ($P = 0.54$). These results indicate that the 3D visualisation software improves student performance irrespective of their spatial ability levels. The questionnaire data indicated that most participating students (97%) found the 3D software superior to plastic models and that the 3D software was an effective teaching resource (Jamil et al., 2019).

4.2.5 Synthesis

The studies included in this review were performed in seven different countries, thus indicating the interest in implementing new digital and imaging resources in anatomy education worldwide. The results of (Petersson et al., 2009) supported the results of earlier studies indicating that using new computer aided tools is well accepted by students (Nieder et al., 2000) and can improve students' learning (St Aubin, 2000; Lynch et al., 2001; McNulty et al., 2004) and spatial and 3D understanding of anatomical structures (Silén et al., 2008).

Students can benefit from using 3D technology resources through long-term retention of gross anatomy information (Peterson and Mlynarczyk, 2016); therefore, new visualisation techniques and devices are a useful supplement to the traditional methods of anatomy teaching. Moreover, 3D digital models are important in cases where limitations exist in teaching students complex structures through dissection or cadavers, such as the structures of the larynx and the middle ear (Nicholson et al., 2006, 2008). Previous studies have also supported the benefits of using tablet-based 3D applications as anatomy learning tools for students (Lewis et al., 2014). New 3D visualisation resources such as VR and AR can increase student engagement and enjoyment of anatomy education, as well as increase their interaction with 3D digital models for improved understanding (Moro et al., 2017). New visualisation applications of VR and AR in anatomy education appear to show great promise as powerful education resources in medical and health science curricula (Moro et al., 2017). TELT can be used to enhance student anatomy and radiology learning when correctly implemented into curricula in order to create an effective learning environment (Webb and Choi, 2014). The use of 3D computer models is likely to reduce the cognitive load associated with the mental reconstruction of different anatomical structures (Sweller, 1988; Paas et al., 2004; Khalil et al., 2005a; Van Nuland and Rogers, 2016b). Additionally, providing students with self-directed learning resources would increase their engagement (Paas et al., 2005; Venail et al., 2010; Kester et al., 2011).

No statistically significant difference ($P > 0.05$) has been observed between students with high and low levels of spatial ability regarding the educational value of 3D digital computer model tools (Ruisoto Palomera et al., 2014). Thus, digital resources can be useful for all students regardless of differences in their spatial ability skills. The use of 3D images helps students understand the sizes and relationships among anatomical structures, as well as individual variations in different anatomical structures (Silén et al., 2008). VR can help students examine the sizes and positions of cardiac structures (Maresky et al., 2019). However the need of physical interaction with a 3D model in medical education is important to understanding its physical structure and to gain a sense of self-confidence and familiarity (Cooper and Taqueti, 2008) as this understanding is important for medical students in different fields of anatomy or surgery (Privett et al., 2010).

RA eLearning can increase student interest in radiology and their enjoyment of continued learning, thus positively increasing their appreciation of radiology in medical practice and potentially stimulating their interest in a radiology as a career (Branstetter IV et al., 2008; Turmezei et al., 2009; Dettmer et al., 2010; Kourdioukova et al., 2011; O'Malley and Athreya, 2012). The literature review identified no studies using both the Secta VT and 3DP models in dissection practical sessions.

4.2.6 Conclusion

This systematic review focused on the recent digital and 3D approaches and resources to teaching anatomy and radiology. The use of different digital and 3D resources improved student understanding of the complex topics of anatomy and radiology. Students had a positive perception of using the new resources in combination with traditional teaching resources. This overview of the value of digital learning approaches and resources may provide a basis for anatomy educators to use these resources at their institutions. Students showed great respect for the ability of these resources to improve their gross anatomy learning and clinical image interpretation. Thus, the findings support the incorporation of such approaches into medical curricula by using digital and 3D resources in learning activities alongside traditional teaching methods to improve learning outcomes.

4.3 3D Printing in Anatomy Education

4.3.1 Background

3D printing (3DP) is a technology currently being effectively utilised in modern medical education as a teaching resource (AbouHashem et al., 2015; Smith et al., 2017). 3DP is an innovative educational tool that can provide a unique method of learning beneficial to both teachers and students. In recent years, 3DP has become increasingly utilised within the medical and biomedical fields as a rapid technique used in research, practice, and education (Li et al., 2017). The first commercial use of 3D printers was in 1980 by Charles Hull (Holzmann et al., 2017). 3DP technology was then developed to be used in many fields, including jewellery making, rocket parts (Shahrubudin et al., 2019), healthcare, surgical training (Li K, 2017) and, in recent years, education (McMenamin et al., 2014). Layer-by-layer fabrication is the key to 3DP technology (Shahrubudin et al., 2019). The International Organization for Standardization (ISO)/American Society for Testing and Materials (ASTM) includes seven 3D printer categories (**Table 4.6**) (Tofail et al., 2018). There are many different type of 3D printers and many different materials and substances used to print 3DP models. Moreover, different software and techniques are used in constructing and printing 3DP models. Material extrusion, vat photopolymerization, material jetting, and powder bed fusion are the most common 3D printer types used in medical education (Shahrubudin et al., 2019). A material extrusion 3D printer can be used to print models in multiple colours and multiple materials. Fused deposition modelling (FDM), developed in 1990 (Shahrubudin et al., 2019), is the most common technology that uses the material extrusion process (Stansbury and Idacavage, 2016). This process begins by building layers of thermoplastic material from the bottom up by heating and extruding thermoplastic filaments from a heated nozzle. The most common materials used in FDM are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC) and polyetherimide (PEI). A single extrusion produces one colour and a dual extrusion using two filaments allows for the use of different colours during the print.

The second 3DP type is the vat photopolymerization process, in which photopolymer, a liquid form of plastic material, is cured by exposure to high energy light such as laser or ultraviolet (UV) (Low et al., 2017). Three types of technology are used in vat photopolymerization: digital light processing (DLP), stereolithography (SLA), and continuous liquid interface production (CLIP) **(Table 4.6)**. SLA is the most common technology used in vat photopolymerization printing. In this process, a platform is deposited in a tank of liquid materials that are cured and hardened by UV or laser to design the required model one layer at a time (Stansbury and Idacavage, 2016), resulting in higher quality and more accurate models.

Material jetting is another 3DP type similar to office inkjet printing. Linear nozzles heated by print heads drop thermoset photopolymers onto the platform. When the drops are in place, a UV light cures the materials to build the model layer by layer (Silbernagel, 2018). ABS, polypropylene (PP), and other photopolymers are material used in material jetting 3D printers. Powder bed fusion 3D printers use laser or electron beams to melt powdered materials together (Shahrubudin et al., 2019). This type of 3D printer uses a thermal process rather than chemical binding to bind the materials.

	3D print type	**Technology used**	**Materials used**	**Summary**
1	Material extrusion (ME)	Fused deposition modelling (FDM)	1- Polylactic acid (PLA) 2- Acrylonitrile butadiene styrene (ABS) 3-Polycarbonate (PC) 4-Polyetherimide (PEI)	Melted thermoplastic materials are deposited layer over layer to build the required model.
2	Vat photopolymerization process (VP)	Stereolithography (SLA)	1- Photopolymer 2- Thermoset polymer resins	Materials are cured to create the model by exposing the photopolymer to UV laser light.
3	Material jetting (MJ)	Multi-jet modelling (MJM)	1- ABS 2- Polypropylene (PP)	Heated print heads deposit plastic resin through linear nozzles that are cured using UV light.
4	Powder bed fusion (PBF)	Selective laser sintering (SLS)	1- Metals	Materials are fused layer by

			2- Ceramics 3- Polymer	layer using laser beams (thermal source).
5	Binder jetting process	Powder bed and inkjet head (PBIH)	1- Polymers 2- Metals 3- Ceramics	Liquid and chemical binding agents are used to join the powder materials together in which each layer is built on top of the finished previous layer.
6	Sheet lamination (SL) and binder jetting (BJ)	Laminated objective manufacturing (LOM)	1- Paper 2- Plastic 3- Metal	Adhesive is used to join the materials layer by layer to form the model.
7	Directed energy deposition (DED)	Laser metal deposition	1- Ceramics 2- Polymers 3- Metals	The required area is melted by laser and a new metallic powder is deposited to create the required object layer by layer.

Table 4.6: Overview of the seven types of 3D printer

For medical and anatomy education purposes, CT and MRI scans should be in digital imaging and communication in medicine (DICOM) format to generate 3DP models (McMenamin et al., 2014; Smith et al., 2017). DICOM files need to be transferred to stereolithography (STL) format using open access software (Meshmixer, Blender) or commercial software (Materialis, Avizo) to begin the segmentation process and adjust the models for printing.

One advantage of 3DP models is that they allow for the processing of MRI and CT scan files to recreate 3D models with the indicated pathology for teaching purposes. In any anatomy department, a member of the department can use open access datasets to retrieve CT and MRI scans in the form of DICOM files and, over time, the department can create a bank of CT and MRI scans. For example, soft breast and rigid mass tumour models can be constructed for increasing student understanding of certain pathology cases (Daniel et al., 2016). In the future, this may provide students with an improved understanding of pathology that they cannot gain in the DR. A cirrhotic liver, for example, can be printed for comparison with a healthy liver for increased educational benefit (Smith et al., 2017). Accurate 3DP models can be made available for students outside of the classroom setting. Self-directed learning sessions using 3D models have been found to have a significant impact on student outcomes (Lim et al., 2016). Some institutions have started to print models of lung, kidney, heart, and breast tumours (Daniel et al., 2016); (Smith et al., 2017).

4.3.2 Aim and review research questions

The main aim of this systematic review is to review the most recent studies and research concerning the use of 3DP models in anatomy teaching and to evaluate their effectiveness. To accomplish this aim, the next questions were developed:

1. How can 3DP models enhance medical student learning of challenging 3D concepts in gross anatomy?

2. To what extent do 3DP models enhance medical student experiences, performance, and understanding of gross anatomy (**Table 3.2**)?

4.3.3 Methods

This review followed PRISMA guidelines to report the findings, which include a flow diagram, protocol guidance, and an inclusion and exclusion check list (Moher et al., 2009; Page et al., 2021).

Searching the database and search terms

An electronic search was performed of the PubMed database. The date was restricted to between 2000 and 2021 since the use of 3DP in anatomy education is a new resource that has only been in use for the last two decades (AbouHashem et al., 2015). Two keyword sets were used, as presented in **Table 4.7**.

Education Type	Technology Used	Targeted sample
Anatomy Education	(and) 3D print	(and) undergraduate
Anatomy Education	(and) 3D print enhance learning	(and) undergraduate
Anatomy Education	(and) 3D print	(and) medical students
Anatomy Education	(and) 3D print	(and) medical education

Table 4.7: Keyword terms used to search for studies included in the systematic review

Inclusion and exclusion criteria of the reviewed studies

All the related articles were initially screened by title and abstract; the full text was then reviewed for all the included articles. The review was focused on anatomy education and anatomy courses, as these are important courses for medical and allied health degrees. All the validated results obtained from students were included, and it was ensured that medical students and medical profession students were the subject of interest in the reviewed studies. Studies that focused on postgraduate students and clinical professions were excluded from the review. The review focused on gross anatomy and clinical imaging, so studies that included embryology or histology were excluded. There were no geographical restrictions, and studies from different countries were included in the review. Only studies between the years of 2000 and 2021 were included. Only studies in the English language were included. The exclusion criteria were as follows (**Table 4.8**):

1	Studies focused on the technical aspects of 3DP models and that did not focus on anatomy education or teaching methods
2	Systematic reviews, narrative reviews, and letters to editors
3	Studies describing the use of non-3DP teaching resources in anatomy education
4	Descriptive studies of the use of 3DP models for clinical situation such as surgical planning

Table 4.8: Description of exclusion criteria

Process of paper selection

All of the selected studies were reviewed using the inclusion criteria mentioned above. The database research outlined in **Figure 4.2** was used to identify the studies. The selected studies were then placed on a table (**Table 4.9**) and the inclusion criteria were applied independently.

Summarising collected data

The main data extracted from the selected studies were the title, authors' names, year of publication, subject area (anatomy), population type and number (medical and allied health undergraduate students), country and university where the study was conducted, methods of evaluation (questionnaire, pre-testing/post testing), study aim, and main results/conclusion. These data were then summarised and organised in a table (**Table 4.9**).

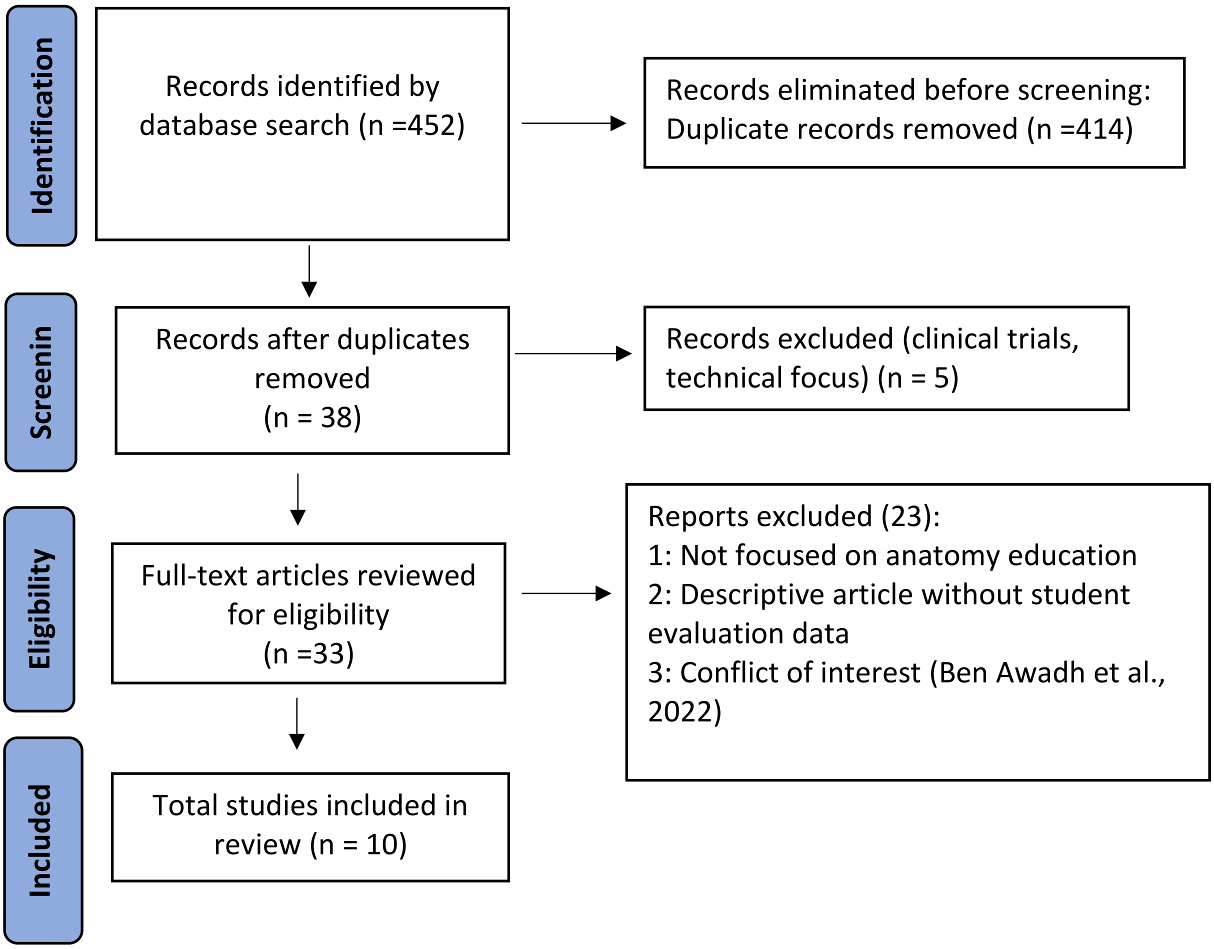


Figure 4.2: Summary of the process followed to identify the studies included in this 3DP models review.

The figure presents the process used to screen articles for inclusion and exclusion following the steps of the PRISMA flow diagram (Moher et al., 2009).

Number	Reference	Title	Targeted sample	Place of the study	Methodology	Study Focus	Analysis & Findings
1	(Lim et al., 2016)	Use of 3D printed models in medical education: A randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy	First-year medical students (n = 53)	Medical School at Monash University (Clayton Campus), Australia	Pre-test and post-test	To assess the effectiveness of 3D printed models compared to cadaveric material.	3D printed models can be high-quality teaching materials. The use of 3DP models for learning external cardiac anatomy resulted in a statistically significant improvement in test scores for the participating students.
2	(Smith et al., 2017)	Take away body parts! An investigation into the use of 3D-printed anatomical models in undergraduate anatomy education	First-year medical students (n = 127)	Brighton and Sussex Medical School (BSMS), University of Sussex, UK	Questionnaire (personal usage) Pre-test and post-test Focus group	To evaluate the educational value and benefits of 3D printed models.	A CT dataset can be used to produce accurate 3DP models. 3DP models can enhance student learning of anatomy.

3	(Wu et al., 2018)	The addition of 3D printed models to enhance the teaching and learning of bone spatial anatomy and fractures for undergraduate students: A randomized controlled study	Medical students (n = 90)	Wenzhou Medical University, China	Gross anatomy and normal regional anatomy test	To investigate 3D printed models as a technique for bone anatomy and fracture versus radiographic images.	3D printers can print accurate anatomical models for use in anatomy education. 3D printed models can improve medical students' understanding of bone anatomy and fractures. Students had a high level of satisfaction when using 3D printed models.
4	(Su et al., 2018)	Three-dimensional printing models in congenital heart disease education for medical students: A controlled comparative study	63 medical students in one class were randomly allocated to two groups (32 students in the experimental group, and 31 the control group)	Xiangnan University School of Medicine, China	Questionnaire (Likert-type) MCQ tests	To explore the efficacy of the use of 3DP models of congenital heart defects in medical education.	An overall improvement of student structural conceptualisation and performance in both test scores and in the questionnaire. Students had a positive perception of using the 3DP model of the heart, which increased their interest in cardiology and cardiac surgery. Some students suggested that some parts of the 3DP models needed to be improved, especially heart

							valves and trabecular muscles.
5	(Mogali et al., 2018)	Evaluation by medical students of the educational value of multi-material and multi-coloured three-dimensional printed models of the upper limb for anatomical education	Fifteen (14 males and one female) second-year medical students.	School of Medicine, Lee Kong, China	Questionnaire (Likert-type) Focus group	Are 3DP models more accurate and realistic for anatomical education? To investigate student perceptions concerning the use of 3D printed models in learning anatomy.	The use of multi-colour and multi-material 3DP models has value and potential for future anatomical education. Students found 3DP models to be valuable sources for learning anatomy. Anatomical accuracy, colour coding, and flexibility were all positive features identified by students.
6	(Backhouse et al., 2019)	Is this mine to keep? Three-dimensional printing enables active, personalized learning in anatomy	Students in the first-year ocular anatomy unit of a Bachelor of Vision Science/Master of Optometry degree (n = 69)	School of Medicine, Deakin University, Geelong, Victoria, Australia.	Questionnaire (Likert-type)	To investigate student insights about the benefits of using personalised 3DP models in learning ocular orbital anatomy.	Student perceptions of using 3DP models in teaching were positive and they reported high levels of enjoyment using the 3DP models in their learning activities. 3DP models were beneficial for student learning, especially when visualising the spatial relationships between the bones of the orbits.

							3D technology can provide students with low-cost and highly accurate and personalised resources that can be used for anatomy learning alongside traditional teaching methods.
7	(Yi et al., 2019)	Three-dimensional printed models in anatomy education of the ventricular system: A randomized controlled study	Second-year medical students (n = 60)	Fujian Medical University, China	Questionnaire (Likert-type) Pre-test and post-test	To design a 3DP model of the ventricular system and to evaluate the learning benefits of 3DP models compared with 3D images and 2D images.	The printing of 3DP models of the ventricular system was successful. 3DP models and 3D images can significantly improve student performance compared with 2D images. Students positively perceived the use of 3DP models compared to 3D images. 3DP models increased student interest and enthusiasm when learning the anatomy of the ventricular system.
8	(Cai et al., 2019)	The effects of a functional three-dimensional (3D) printed	First-year medical students (n = 35).	National University of Singapore (NUS), Singapore	11-question quiz	To develop a 3DP knee-joint simulator model and evaluate the impact of 3DP models on the spatial understanding of	3DP simulator models improved the spatial anatomical understanding of the medical students.

		knee joint simulator in improving anatomical spatial knowledge				medical students in relation to human anatomy. The study also assessed the elimination of sex-related differences in learning human anatomy and spatial understand.	Both male and female students had better outcomes when using 3DP simulator models and no significant differences in the performances of males and females were found.
9	(Tanner et al., 2020)	A three-dimensional print model of the pterygopalatine fossa significantly enhances the learning experience	Sophomore and junior undergraduate students enrolled in the FAME pre-medicine undergraduate programme at UTSA (n = 17), graduate students at the Master of Biomedical Science programme (n = 37), first-year dental students enrolled at the UT Dental School (n = 26), first-year	The University of Texas at San Antonio (UTSA), UT Health, San Antonio and the University of Incarnate Word (UIW), San Antonio, USA	Pre-quiz and post quiz Satisfaction Survey	To evaluate the use of 3D printed models of the pterygopalatine fossa (PPF) in improving student knowledge of PPF anatomy.	3D printed models of the PPF significantly improved student knowledge in randomized controlled groups. 3D printed models are a cost-effective, portable, kinaesthetic learning tool in medical education. Students enjoyed using 3D printed models for learning.

			physical therapy students at UT Health, San Antonio (n = 8), first-year medical students enrolled at the Long School of Medicine at UT Health, San Antonio (n = 30).				
10	(Tripodi et al., 2020)	The impact of three-dimensional printed anatomical models on first-year student engagement in a block mode delivery	First-year osteopathic students (n = 111)	Victoria University, Melbourne, Australia	Questionnaire (Likert-type) Focus group interview	To examine if using 3DP models of the bones printed in-house increases the engagement of first-year osteopathic students in block-mode delivery.	3DP models increase student engagement in anatomy classes. 3DP models increase student academic confidence and performance by allowing them to take responsibility for their own learning. 3DP models help students to prepare for vivas and exams. Students had a positive perception of using 3DP models as a learning tool to help them in

							knowledge gain and retention.

Table 4.9: Summary description of the 10 studies included in this review (organised by date of publication)

4.3.4 Results

Evaluation of the studies included in this review

The database research, which followed the approach outlined in **Figure 4.2**, was performed using PubMed and resulted in 452 manuscripts. Of these, 38 were identified after the removal of 7 duplicate studies. The inclusion and exclusion criteria were applied, and 5 articles were excluded for the following reasons: Three described clinical trials rather than anatomy education; one was published by the researcher (Ben Awadh et al., 2022) and was, therefore, excluded to avoid a conflict of interest; and one reported a pilot study, which did not meet the inclusion criteria. As a result, a total of 33 articles were considered for eligibility. Of these, 23 studies were excluded because they were illustrative reports of technical methods and techniques for making 3D printed models, they investigated the benefits of 3DP modelling for surgical planning and medical staff, they did not focus on gross anatomy education, or they did not investigate the educational effectiveness of 3DP models. Thus, a total of 10 articles met the criteria to be included in the review (**Figure 4.2**). Of the 10 studies, the oldest (Lim et al., 2016) was published in 2016, one article was published in 2017, the majority (n = 6) were published between 2018 and 2019, and two were published in 2020.

The majority of the studies were conducted in the People's Republic of China (n = 4; 40%), followed by Australia (n = 3; 30%) and the United Kingdom (n = 1; 10%). Of the other two studies, one was conducted in the Republic of Singapore (n = 1; 10%) and one in the United States of America (n = 1; 10%). The diversity of the studies shows that there is international interest in the use of 3DP models in anatomy education.

Further analysis was performed regarding the type of participants. Most of the studies had medical students as the main study sample (n = 7; 70%). Moreover, one study covered the effect of 3DP model usage in anatomy education among osteopathy students (n = 1, 10%). The participants in the remaining two articles were mixed-major students, one of which included students enrolled in Bachelor of Vision and Master of Optometry programmes, while the other included more than five different student majors in the study sample (**Table 4.9**). Eight of the studies (80%) had fewer than 100 participants and the remaining two (20%) had more than 100 participants.

The main teaching methods used in these studies were traditional teaching methods, including lectures, dissection practical sessions, and the use of 2D anatomical images. All studies included the use of 3DP models to investigate their effectiveness in anatomy education and to investigate student perceptions of the use of 3DP models as teaching resources. It was necessary to include studies that collected experimental or self-reported data as many systematic reviews only use one or the other. The targeted sample, place of study, evaluation methodology, aims, and analysis/conclusion are summarised in **Table 4.9.** All the studies included in this review focused on the impacts and benefits of implementing 3DP models as a teaching tool in anatomy education.

3D printed models in medical education

The first study (Lim et al., 2016) compared student performance when using 3DP models for learning without prior formal cardiac anatomy teaching. The authors described their experimental study design as a double-blind randomised controlled study. In the study, the participants were divided to three groups. The first group used 3D printed models only. They were given a model with the great vessels, one without the great vessels, and a model angiogram of the coronary arteries. The second group used cadaveric material only. They were given one heart with the great vessels and one without, and they also used a plastinated prosection. The third group used both cadaveric materials and 3DP models. Following a pre-test, a 15-minute introductory lecture was given by an external teacher who was not one of the investigators, and the participants were randomly divided into three groups. All the participants were then provided with the same task sheet with the same learning objectives, and they were given 45 minutes to study and work through the objectives using the material provided, as described above. Finally, a post-test was administered that utilised labelled images to test structure function, identification, and their relationship. The results showed a significant increase in test results in the 3DP model group only.

3D models in anatomy education

The second study (Smith et al., 2017) also divided participating medical students who took a module tutorial on surface anatomy into two groups: the control group, who used 2D anatomical images, and the intervention group who used 3DP models only. A mixed-methods approach was applied in the study to evaluate the benefits and disadvantages of using 3DP models in human anatomy education. Experimental pre-testing and post-testing, focus groups, personal use evaluation questionnaires, and faculty evaluations were all implemented by the researchers. The findings showed that students in the 3DP model group had a significant increase in performance ($P = 0.0001$) compared with students in the 2D images group. Focus group analysis found that students had overall positive perceptions towards the use of 3DP models.

The addition of 3D printed models in teaching anatomy

Medical students (n = 90) participated in a study performed at Wenzhou Medical University, China (Wu et al., 2018). The students were divided into two groups: the control group, which used traditional clinical images presented in a PowerPoint slideshow presentation, and the intervention group, which used 3D printed models combined with the PowerPoint slideshow presentation. Student performance was then evaluated in a post-test with a satisfactory visual scale questionnaire. The analysis showed no significant difference between the two groups in the final exam scores for either the gross anatomy course ($P > 0.05$) or the regional normal anatomy course ($P = 0.574$). However, detailed analysis showed that the test score performance for the pelvis and spine sections in the traditional imaging group was significantly lower than that of the 3DP model group ($P < 0.001$). Moreover, the mean score for the visual satisfaction questionnaire was significantly higher ($P < 0.001$) for the 3DP model group, suggesting that students had more satisfaction when using the 3DP models than when using traditional radiographic images.

Heart education and 3D printed models

(Su et al., 2018) aimed to explore the efficacy of the use of 3DP models of congenital heart defects in medical education. Participating medical students (n = 63) were divided in two groups: an experimental group, which received a seminar in ventricular septal defects (VSD) that integrated 3DP models of the heart (n = 32), and a control group, which received the same VSD seminar but used clinical images and animations (n = 31). The same lecturer led the seminars for each group. At the end of each seminar, the participating students completed multiple choice tests and a 10-point Likert-type questionnaire. Results showed that the test scores for the experimental group were statistically higher when compared with those of the control group ($P < 0.05$). In addition, the questionnaire results showed a significant improvement in learning VSD and better seminar outcomes in favour of the experimental group in VSD learning ($P < 0.0001$).

Multi-material and multi-coloured 3DP models and anatomy education

(Mogali et al., 2018) aimed to investigative the educational benefits of 3DP in anatomy learning from the student perspective. The authors hypothesised that 3DP models could be used with other resources to improve anatomy education. In a revision session on the upper extremities, students were given both plastinated upper limb prosections and 3D printed models of the arm. An overview of the session's learning objectives was given to the students by the instructor in the first 10 minutes. The participating students (n = 15) then had 40 minutes of self-study. During this time, they used both the 3DP models and the plastinated prosections to cover the materials in their practical handout. The last 10 minutes of the session was used for questions and clarification. At the end of the session, students were given a five-point Likert-type questionnaire. A focus group later gathered more information from the students. The findings showed that the students had positive perceptions about the effectiveness of 3DP models as learning resources in anatomy teaching. An analysis of the focus group themes showed that the students appreciated the benefits of colour-coding and the accuracy of the size as presented in the 3DP models (Mogali et al., 2018). However, students also commented that some parts of the 3DP models were not as realistic as the plastinated prosections (Mogali et al., 2018).

Personalised 3DP model learning activities

Evaluating student perceptions of using 3DP orbit models in anatomy education and investigating student engagement were the focus of (Backhouse et al., 2019). Every student (n = 81) enrolled in the first-year ocular anatomy unit was provided with their own 3D printed orbit. During the practical session, students were asked to trace the sutures using a black marker and to colour the six orbit bones using a different colour for each bone. The students had 15 minutes to complete the colouring task. During the task, students had access to a variety of resources, including lectures, notes, and anatomical models to assist them. To encourage peer learning, students needed to complete a table with three of their classmates to identify the colour coding of the bones used in the activity. Two months after this practical session, students were given a Likert-type questionnaire. Only 69 students completed the questionnaire. The results showed that the majority of students found that 3D printed models of the orbits made learning more interesting and the 3D printed orbit improved student understanding of the spatial relationship between the different structures of the orbits. The use of the 3D printed orbit models suited the learning style of the majority of the participating students. Students made negative comments about the fidelity and size of some features of the models. Some students would have preferred the models to be bigger. Other students commented that some of the model features were hard to identify, such as some of the sutures (Backhouse et al., 2019).

Anatomy education of the ventricular system and 3DP models

A 'randomised controlled' experimental study was performed by (Yi et al., 2019) to evaluate the learning benefits of 3DP models of the ventricular system compared with 3D images and 2D images. Second-year medical students (n = 60) were randomly divided into three groups: the 3D image group (3DIs), the 2D image group (2DIs) and the 3DP model group (3DPMs). Students in both the 3DIs and the 3DPMs groups showed a significant improvement compared with the 2DIs group in terms of practice post-test scores. In the student's evaluation questions, the 3DPMs group performed better than the 3DIs group in the evaluation items of "enjoyment" and "attitude". Interestingly, the study showed no significant difference (P > 0.05) between male and female students in any test scores or evaluation questions.

Learning the knee joint using 3DP models

Only one study (Cai et al., 2019) in this review aimed to develop a 3D printed dynamic and functional knee-joint simulator model and to evaluate the impact of that 3DP model on the medical students' spatial understanding in relation to human anatomy and whether sex-related differences in learning existed. Analysis of the results showed that students who used the 3DP knee-joint simulator performed significantly better than those who used didactic resources (lecture and skeleton models). The females in the study achieved greater improvements with regard to learning outcomes when compared with the males in the same group. However, further statistical analysis performed using two-way ANOVA showed that the sex of the student had no influence on learning outcome (P > 0.05).

3DP models of the pterygopalatine fossa

One study in the review evaluated student performance and knowledge of the pterygopalatine fossa (PPF) with respect to student anatomy experiences (Tanner et al., 2020). The participating students were divided into two cohorts: cohort I included students with no PPF anatomical experience (n = 88) and cohort II included students who received a formal PPF lecture (n = 33). Students in both cohorts were divided in two groups: a control group that used traditional teaching resources (they were provided with a half skull) and an intervention group provided with 3DP models of the PPF. Following a pre-test, the students undertook a self-directed study session for 40 minutes, after which they completed a post-test. The results showed a significant improvement in cohort I between students who used traditional resources and those who used 3DP models of the PPF. However, the results for the cohort II students with PPF experience showed no significant difference between the mean scores of the control group and the intervention group. Data analysis of the satisfaction survey showed that the intervention groups (3DP model users) from both cohort I and cohort II reported high levels of satisfaction when using 3DP models.

Student engagement and 3DP models

The most recent study (Tripodi et al., 2020) used in-house printed 3D bones to increase student engagement and interaction in class. Students were given a set of 3DP models of the upper limbs that included the clavicle, scapula, humerus, ulna, radius, carpal, and metacarpal bones. Students had four hours of in-class activities that included bone orientation and identification using the 3DP bone models. The students were also encouraged by their instructors to repeat these class activities at home or in their spare time to prepare them for assessment. Two mixed-methods approaches were used in the study to evaluate the benefits of 3DP models. The first evaluation method was a five-point Likert-type questionnaire and free-text questions to evaluate student usage, perceptions and engagement when using 3DP models. The second evaluation method was a focus group interview conducted with sets of questions to gather more information from the participating students. Questionnaire response analysis showed that the majority of students had a high level of usage and engagement with the 3DP models and a positive overall benefit from using them ($P < 0.001$). The majority of students reported an improvement in their viva, which was a final lab-based oral anatomy examination in which each student had 15 minutes to present three anatomical specimens to the examiner ($P < 0.001$). The majority also reported increased confidence levels in their assessment preparation when using 3DP models ($P < 0.001$). Moreover, the students had positive perceptions regarding their ability to take the models away from the university and use them outside of class time, which helped them to learn independently in their own time ($P < 0.001$). The focus group interviews and free-text answers to the questionnaire identified four themes. The first theme was behavioural factors. The students reported that using 3DP models improved their performances in the unit and allowed them to enhance their results in general. The second theme was psychological factors, as students stated that their confidence levels increased after using 3DP models, allowing them to feel and identify important bony structures and landmarks in preparation for their viva. The third theme was socio-cultural factors. The participating students commented that the 3DP models were more effective learning tools than slides and images. The fourth theme was holistic factors. The students reported that 3DP models can be a useful resource not only for anatomy but for other subjects, such as clinical skills and biomechanics.

4.3.5 Synthesis

Most of the articles in this review were published in the five years preceding the review during a time of major growth in the use of 3DP models in anatomy education for medical and allied health students. In the last two decades, 3D printers have been utilised in many fields including the medical field for both educational and clinical use (AbouHashem et al., 2015). The studies emerged from several countries across different continents, indicating international interest in the benefits of 3DP model use in anatomy education. In anatomy education, 3DP models can be made available as high-quality teaching resources that solve some of the financial, ethical, and cultural issues posed by cadaveric specimens (Lim et al., 2016). Student knowledge and performance can be enhanced by implementing 3DP models in anatomy education (Smith et al., 2017). Students were more satisfied when using 3DP models than when using traditional radiographic materials (Wu et al., 2018). 3DP provides students with true 3D models that they can manipulate and interact with to enhance their understanding of spatial relationships compared with 2D resources such as diagrams, clinical images, and conventional echocardiography, all of which can make the understanding of the 3D aspects of human anatomy challenging, for beginner learners in particular (Su et al., 2018). (Mogali et al., 2018) were the first to report the use of multi-material and multi-coloured 3DP models of the upper limbs obtained from plastinated prosection DICOM data. The study showed that students had positive views with regards to the colour coding of the models, which helped in the identification of different anatomical features and structures. The authors claimed that student stress about damaging models during use can be reduced with 3DP models, thus encouraging more interaction and engagement to enhance the tactile experience of learning (Mogali et al., 2018). Students also expressed the value in taking 3DP models outside the university, which helped them to study at their own pace to improve their learning (Backhouse et al., 2019). Cadaveric dissection is considered an effective method for learning anatomy. However, some anatomical structures are difficult to study or visualise using dissection. 3D printers have the advantage of printing 3DP models of structures that are difficult to see during dissection, such as the ventricular system and the PPF (Yi et al., 2019; Tanner et al., 2020). 3DP models can also be used to reduce the cognitive load of complicated anatomical information, thus enhancing understanding of spatial information (Cai et al., 2019). The same study showed that sex was not a contributing factor to improvements in student learning outcomes. Some of the studies included in this review also mentioned the disadvantages of 3DP. Printing times can be long for some models, taking more than 30 hours for one model in some cases (Yi et al., 2019). The detail and accuracy of small structures, such as the heart valves, needs to be improved for better presentation (Su et al., 2018).

4.3.6 Conclusion

This systematic review illustrated the use of 3DP anatomical models in anatomy education as an effective teaching resource over the past five years. Many universities around the world have implemented 3DP models in their anatomy teaching curricula having evaluated their benefits to student performance and engagement, as evidenced in the articles included in this review. 3DP is an effective technology currently being effectively utilised in modern medical education (AbouHashem et al., 2015) and fulfils all these requirements. 3DP is an innovative educational tool that can provide a unique method of learning beneficial to both teachers and students. In recent years, 3DP has become increasingly utilised within the medical and biomedical fields as a rapid technique used in research, practice, and education (AbouHashem et al., 2015). 3D printers located in institutional anatomy and clinical-skills departments allow the creation of 3D models from CT and MRI scans in the form of DICOM images that can be used for teaching (McMenamin et al., 2014). This will allow students to better understand the three-dimensionality of anatomical structures (O'Reilly et al., 2016). Students will have the ability to compare what they see in real specimens with 3DP models that can be taken outside the DR (Smith et al., 2017). Some pathologies can be better understood by students with 3DP models, especially if no prosections exist that show the pathology (Daniel et al., 2016). Moreover, 3DP printers can print models of anatomical structures that are not easy to visualise on cadavers, such as the bones of the middle ear (AbouHashem et al., 2015). Implementing 3DP models with traditional teaching methods allows students to develop their confidence, improve their spatial understanding of complex anatomy, and reduce their stress and anxiety levels when dealing with cadaveric materials. The main conclusion, therefore, is that 3DP models are an effective educational resource and a useful self-directed learning resource that can enhance human anatomy education.

4.4 Digital Embryology Resources

4.4.1 Background

Embryology is the study of early development (Brenton et al., 2007). It is an important subtopic of human anatomy essential for medicine and medical science students (Carlson, 2002). The study of embryology also provides an understanding of abnormal development and birth defects (Carlson, 2002). Moreover, understanding the pathogenesis of congenital malformation requires the understanding of complex morphogenetic processes that happen during embryonic development (de Bakker et al., 2012). For these reasons, embryology is a major part of the human anatomy curriculum (Holland et al., 2019). Embryological development of the human embryo is a very complex and challenging topic (Labrousse et al., 2015). Students need to understand the simultaneous changes and different stages in embryo development to proceed with the study of human embryology (Moraes and Pereira, 2010). Embryology is an important part of anatomy courses because it allows students and health professionals to understand anatomy and its variations and the reasons for birth defects (Beale et al., 2014). Students find these developmental processes difficult to understand, especially when these processes have to be visualised in 3D and traditional teaching methods (e.g., lectures, textbooks) are limited to two dimensions (Moraes and Pereira, 2010). Furthermore, the time available to deliver clinically relevant embryology teaching in medical degree programmes has decreased. Medical students are required to have good embryology knowledge to understand normal and abnormal human development and to understand malformation to ensure better clinical diagnosis and surgical treatments (Moraes and Pereira, 2010).

The rapid 3D developmental changes that occur simultaneously at the microscopic scale make embryology difficult to teach and to understand (Yamada et al., 2006). 3D and VR resources are useful for teaching dynamic phenomena in morphological science, especially in the areas of anatomy and embryology (Arraez-Aybar et al., 1994; Nieder et al., 2000). Due to teaching-time reduction and the difficulty of the topic presented, universities are aiming to provide additional teaching resources to those currently used (e.g., lectures, textbooks) in order to improve students' experiences and understanding of human embryology, allowing students to enhance their self-learning abilities (Beale et al., 2014).

A major concern is that, in recent years, students have focused more on molecular biology, making them less concerned with embryology (Hamilton and Carachi, 2014; Moxham et al., 2016). This may result in poorer embryology knowledge among graduate medical students.

The main goal for most anatomy and embryology instructors is the most effective use of teaching resources to allow students to process information and enhance their knowledge (Evans, 2011). Embryology can be challenging for students, especially when using static and 2D images to explain detailed dynamic changes (Marsh et al., 2008). Moreover, there is no ideal method for teaching and learning embryology, so every educational institute develops its own embryology teaching methods depending on its own learning outcomes and curriculum objectives (Al-Neklawy, 2017).

4.4.2 Digital embryology systematic review aim and research questions:

The main aim of the present systematic review was to review the most recent studies and research concerning embryology teaching resources and to evaluate their effectiveness. To achieve this aim, the following questions were developed:

1. What teaching resources are used to enhance the learning of challenging 3D concepts and processes in embryology?

2. To what extent do teaching resources enhance medical student experiences, performance and understanding of embryology?

4.4.3 Methods

The present review followed PRISMA guidelines to report the findings, which included a flow diagram, protocol guidance, and an inclusion and exclusion check list (Moher et al., 2009; Page et al., 2021).

Searching the database and search terms

An electronic search was performed of the PubMed database. The date was restricted to between 2000 and 2021 to identify new resources and studies focusing on embryology education and learning in the last two decades. The database research combined search terms that included education type, targeted sample, and resource type (**Table 4.10**).

Education Type	Technology Used	Targeted sample	Results
Embryology education		(and) undergraduate	120
Embryology	(and) digital enhance learning	(and) undergraduate	2
Embryology	(and) technology enhance learning	(and) undergraduate	2
Embryology education	(and) digital resources	(and) undergraduate	1
Embryology learning	(and) technology	(and) undergraduate	13
Embryology learning	(and) technology	(and) medical students	18
Embryology education	(and) technology	(and) medical students	38

Table 4.10: Keyword terms used to search for studies included in this systematic review

Criteria for inclusion and exclusion of reviewed studies

The titles and abstracts of all related articles were screened, and then the full text was reviewed for all included articles. In the review, any study that included embryology without educational intervention was excluded, as the focus of the review was embryology education and learning. There were no geographical restrictions and studies from different countries were included in this review. Only studies in the English language were included in the systematic review. The studies that met these inclusion criteria and were included in the review are presented in **Table 4.11**. The database research is outlined in **Figure 4.3.**

Description	Inclusion criteria
Data	All appropriate papers available in this field between the years of 2000 and 2021.
Language	Only studies in the English language will be included in the systematic review and any study reported in a language other than English will be excluded.
Study Type	Studies that examine embryology education and learning resources.
Participants	Medical and health profession students will be included in the review.
Defining quality	We will include all validated results regarding students' perceptions, ensuring that medical students and medical profession students were the subject of interest in the studies reviewed.

Table 4.11: Description of the inclusion criteria in this systematic review

Process of paper selection and data extraction from the selected studies

All of the selected studies were reviewed using the inclusion criteria mentioned above (**Table 4.11**). The selected studies were then placed in a table (**Table 4.12**) where the main data were extracted from the selected studies. The main data were the title, authors, year of publication, subject area (embryology), population type and number (medical and allied health undergraduate students), country and university where the study was conducted, methods of evaluation (questionnaire, pre-testing/post testing, focus group), study aim, and main results/conclusion. The data were then summarised and organised in a table (**Table 4.12**). A total of 194 articles were identified by the database search following the steps outlined in **Figure 4.3**. After removing duplicates studies (n = 39), 154 studies were included for screening. A total of 21 were eligible for full text screening after applying the inclusion and exclusion criteria shown in **Figure 4.3**. Finally, only seven articles met all the criteria for inclusion in the review.

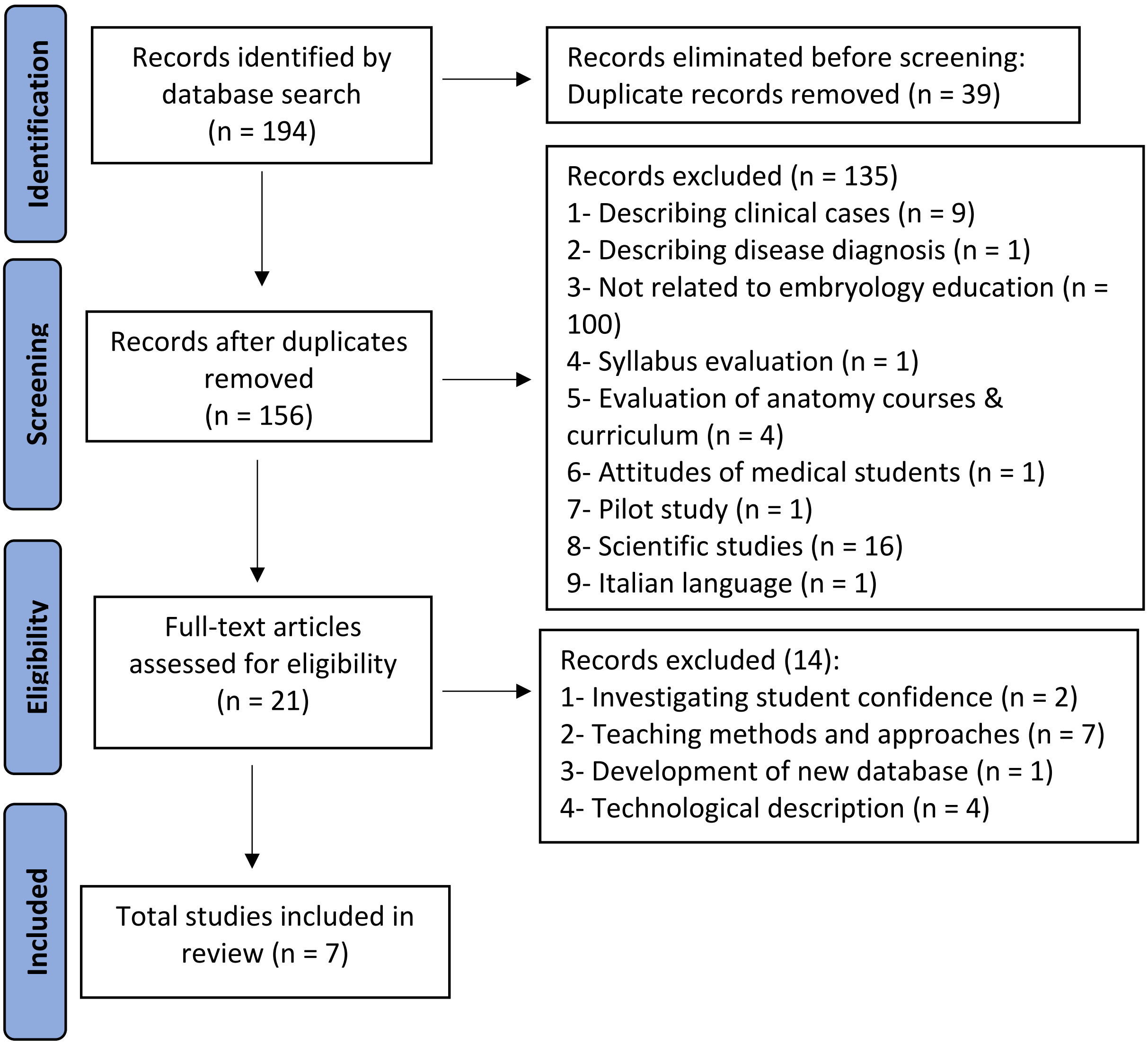


Figure 4.3: Summary of the process followed to identify the studies included in this review.

The process presented in the form of a PRISMA flow diagram (Moher et al., 2009).

Number	Reference	Title	Targeted sample	Place of the study	Methodology	Study Focus	Analysis & Finding
1	(Marsh et al., 2008)	Medical student retention of embryonic development: Impact of the dimensions added by multimedia tutorials	Medical students Short-term study: first-year medical students (class 2009 n = 29), (class 2010 n = 47) Long term first-year medical student (class 2009 n = 69, class 2010 n = 76, class 2010 n = 59)	University of Cincinnati, Ohio, United States of America	Survey (evaluation survey) Quiz	To develop web-based learning modules that blend and combine Animated 3D graphics, 3D models, embryonic development, and animated 2D graphics	The participating students had a positive impression of using animated modules. The animated modules improved student performance and understanding of the embryologic folds that cannot be seen or understood by use of textbooks or 2D images.
2	(Moraes and Pereira, 2010)	A multimedia approach for teaching human embryology: Development and evaluation of a methodology	First-year medical students: interview (n = 50) and survey (n =103)	State University of Campinas, Campinas, Brazil	Survey (Likert-type) Interviews (semi-structured) Knowledge exams	To develop and evaluate the use of multimedia resources in embryology teaching	The teaching methods used in the study had many benefits for teaching and learning the complex topics of embryology.

3	(Abid et al., 2010)	Traditional versus three-dimensional teaching of peritoneal embryogenesis: A comparative prospective study	Medical students (n = 165): (n = 81, Tunisia) (n = 84, France)	Sfax, Tunisia and Paris- Descartes, France	Evaluation test	To compare the teaching effectiveness between traditional chalk teaching and 3D teaching methods in terms of short-term memorisation of peritoneal embryogenesis	The 3D technique was found to be more effective in teaching peritoneal embryogenesis compared to traditional teaching methods. Using the 3D technique for the visualization of dynamic phenomena showed greater benefits.
4	(Evans, 2011)	Using embryology screencasts: A useful addition to the student learning experience	Undergrade medical students	Sussex University, Brighton, United Kingdom	Questionnaire (Likert-type) Written examination	To evaluate student perceptions of the use of embryology screencasts	Embryology screencasts are a useful resource for learning embryology.
5	(Beale et al., 2014)	A retrospective look at replacing face-to-face embryology instruction with online lectures in a human anatomy course	First-year medical students (2007, n = 149) (2008, n = 149) (2009, n = 150)	School of Medicine at Texas Tech University Health Sciences Center, Texas, United States of America	Survey (Likert-type) Comparison of examination performance	To compare the educational benefits between face-to-face lectures and online recorded lectures	Both face-to-face lectures and online recorded lectures provided the same educational benefits and there was no significant difference in performance when the two teaching methods were compared.

6	(Al-Neklawy, 2017)	Online embryology teaching using learning management systems appears to be a successful additional learning tool among Egyptian medical students	First-year medical students (n = 100)	Ain Shams University, Cairo, Egypt	Survey (Liker-type)	To evaluate the benefits of using online teaching for embryology using a learning management system	The virtual classroom supported student learning.
7	(Koscinski et al., 2019)	Videos for embryology teaching, power and weakness of an innovative tool	Students of the health fields, including medical, pharmaceutical, dental, and paramedical.	University de Lorraine, France	Survey (Likert-type) Tests	To evaluate student perceptions and performance when engaged in short videos of an embryology process and whether this motivates and helps students in learning and understanding embryology	Students had positive perceptions of using videos in embryology teaching, which increased their interest in learning embryology. The use of multimedia learning resources with traditional lectures can help students with long-term memorisation.

Table 4.12: Summary description of the seven studies included in this review (organised by the date of publication)

4.4.4 Results

Summary of the included articles

Following the steps outlined in **Figure 4.3**, a total of 194 studies were identified. Thirty-nine articles were removed because they were duplicate studies. A further 135 manuscripts were excluded after applying the inclusion and exclusion criteria (**Table 4.11**). The remaining 21 articles were considered for full eligibility, and 14 of these were excluded for the following reasons: investigating student confidence but not performance or perceptions (9.5%; 2 of 21), teaching methods and approaches (33%; 7 of 21), development of new databases (4.7%; 1 of 21) and technological description (19%; 4 of 21). Finally, seven articles met the criteria to be included in this review (**Figure 4.3**). The first study (Marsh et al., 2008) in this review was published in 2008. Two articles were published in 2010, and only one article was published in 2011. Moreover, the majority of the studies (n = 3) were published between 2014 and 2019. Most of the studies were performed in the United States of America (n = 2; 28.5%) and France (n = 2; 28.5%), followed by the United Kingdom (n = 1; 14%).

Of the remaining two studies, one was conducted in Brazil (n = 1; 14%) and the other in Egypt (n = 1; 14%). Further analysis was performed regarding types of participants. Most of the studies had medical students as the main studied sample (n = 6; 85%). Only one study investigated the use of videos for students of health studies, which included medical, pharmaceutical, dental, and paramedical students (**Table 4.12**). The studies included in the review implemented different embryology teaching resources to investigate student perceptions and performances when learning complex embryology topics.

Embryology learning by web-based animated resources

In the first study (Marsh et al., 2008), the authors focused on creating a multimedia resource to teach areas of embryology that are difficult to teach using textbooks or lectures. A web-based animated module consisted of animated 3D graphics and 3D models that students could manipulate independently to review embryonic development, and animated 2D graphics, including 2D cross-sections representing different ‘’slices’’ of the embryo, animated in parallel to enhance student understanding. The study was divided in two parts: a short-term retention study and a long-term retention study. For the short-term retention study, the participating students were divided randomly into control and intervention groups.

Students in both groups attended a lecture about embryonic folds, but only the intervention group had access to the multimedia animated modules. After the lecture, both groups completed a 14-question quiz. For the long-term study, the participating students were tested at the start of a review session. The test questions were different from the short-term study test questions. The control group continued to have no exposure to the animated module while the intervention group were exposed to the animated module. The short-term study results analysed using the t-test showed a statistically significant improvement in the intervention group compared to the control group (P = 0.02). Student comments indicated that the use of animated resources increased their understanding of the complicated developments during embryonic folding. The same study was repeated for another first-year medical student cohort with no prior embryology knowledge. The results showed a small improvement for students in the intervention group, but the improvements were not statistically significant. In the long-term study, the participating students were tested several months after they had covered embryonic folding. Some of the students had participated in the short-term study, while others were not part of the study from the start. For the control group, students studied embryologic folds without using the animated resources and completed a quiz 16 weeks after the lecture. The intervention group consisted of two groups of first-year medical students – class of 2009 and class of 2010. The class of 2009 studied embryology twice, using the animation material once. They then completed the quiz 16 weeks after the embryology lectures.

The results showed no significant improvement when the control group was compared with the intervention group for the class of 2009. Meanwhile, the intervention group of the class of 2010 covered embryology twice, using the animated materials both times. They were tested after 16 weeks, and the results showed a significant improvement when compared with the control group. An evaluation was conducted to gather students' perceptions of the use of animated materials. The majority of students were positive about their use, stating the materials were easy to use, helped in understanding material that cannot be seen in textbooks, and they liked the different perspectives, such as 3D animations. A survey was sent to the anatomical faculty of different medical schools and the majority of faculty members who responded to the survey gave positive feedback concerning the animation module.

Multimedia resources and embryology learning

The development of multimedia resources and an evaluation of their benefits was the aim of (Moraes and Pereira, 2010). The multimedia resources used in the study included static graphics and animation and interactive software that included clinical histories, images, films, and animation. All the multimedia materials were used to show normal development, abnormalities, and malformations in a series of embryology lectures. The first part of the lecture covered the development of the body using videos and animations. In the second part, instructors covered the clinical history of some cases using microscopic, ultrasound, and autopsy images. Additional post-lecture activities were performed by the students using multimedia interactive software to study the material covered. The students had to take seven exams to assess their knowledge gain from studying embryology. The first-year medical students participating in this study evaluated the use of multimedia teaching resources by semi-structured interview (n = 50) and survey (n =103). In general, text-end survey questions and interview responses showed the students had positive perceptions of the materials used in teaching. However, there were negative responses from a student who stated that the lectures were too long, making it hard to concentrate, that the number of 3D images was limited, and that the clinical case images were disturbing (Moraes and Pereira, 2010).

3D techniques for teaching embryology

A survey of 165 medical students from the Medical Faculty of Sfax, Tunisia (n = 81) and from the Paris-Descartes Faculty of Medicine, France (n = 85) was conducted by (Abid et al., 2010). The participating students were randomly separated in two groups. One group was taught using 3D techniques (3D group, n = 85) and the other group was taught using traditional chalk techniques (CL group, n = 80). The material covered peritoneal embryogenesis and none of the students had pre-existing embryology knowledge. Traditional resources included chalk and blackboard while the 3D resources included 3D illustrations and simulations with an interactive multimedia DVD. Students in the 3D group could use the DVD only once as it was not freely accessible. Both groups completed the 60-minute course followed by a test containing 34 short-answer questions, 20 of which focused on static phenomena and 14 of which focused on dynamic phenomena (rotation of the umbilical ansa, formation of the omental pouch). The tests were collected and corrected, and the overall results were significantly better for the 3D group than for the CL group. In regard to the static phenomena test questions, no significant differences were found between the 3D group and the CL group regarding rate of correct answers. However, for the dynamic phenomena, the 3D group had a significantly higher rate of correct answers than the CL group. Finally, there were no significant result differences between the French students and the Tunisian students in any section of the study.

Teaching embryology by screencasts

A study by (Evans, 2011) investigated medical student perceptions of the use of embryology screencasts in the Brighton and Sussex Medical School. Embryology was taught in lectures and the students had access to a selection of videos/DVDs and CD-ROMs covering embryology. The students were given no practical sessions to cover the embryology elements of the course, so the development of new resources was important. Five sets of screencasts with a review quiz were created for this study (Evans, 2011). The screencasts consisted of modified PowerPoint presentations of the lectures with custom animations for important aspects in order to increase visual stimulation. In the same screencasts, audio recordings were made to match the PowerPoint presentation to produce a visual-audio cast. The screencasts, in web-format, were then uploaded to the managed learning environment. The screencasts were made available to students three days before the lecture. Students could access the screencasts at any time through the managed learning environment only, as they were in non-saveable format. Students had access to the screencasts until the end of the module, at which time they had a questionnaire and a written examination. The results were divided into three categories: student use, student reaction, and student attainment. Student use was measured by the number and timing of downloads. On average, each student downloaded the screencasts three times and the most popular time to access and download was at 8 pm on Wednesdays. A Likert-type feedback questionnaire for each aspect of the module was completed by 112 students (87% of the cohort).

The results showed overall positive student perceptions towards all the lectures. Both the embryology lectures and the embryology screencasts were well received by the students and no statistical differences between lectures and screencasts were found. Only 50 students had specific comments about the embryology screencasts. These comments were positive. Students found the screencasts useful for learning, that they supported the lecture, were great for revision and helped dyslexic students. However, students also suggested improvements, including an increase in the number of screencasts, clearer and slower narrative, and improved spatial understanding. Student attainment was measured by performance in the written exam. The results showed significant improvement compared with results from the previous year, when no embryology screencasts were used.

Online lectures to teach embryology

An investigation of the benefits of online lectures to teach embryology was conducted by (Beale et al., 2014). Thirteen embryology lectures were digitally recorded, resulting in 14 recorded lectures. The same instructor who gave the face-to-face lectures recorded the digital lectures, which could be viewed online. The learning objectives and embryology questions were the same for both the face-to-face lectures and the digitally recorded lectures. In the academic years 2008 and 2009, face-to-face embryology lectures were replaced with recorded lectures, which were shown on the student calendar as independent study sessions (ISS). Once a recorded lecture was uploaded, students had open access to the video at any time and at any place throughout the course. Viewing the videos was not required, but the students were expected to access the recorded lectures. At the end of each unit, the students had an examination consisting of 60 multiple choice questions. There were also three summative unit examinations. In each unit examination, 17%–20% of the questions focused on embryology and covered the embryology learning objectives. The study compared student examination performances in three years: 2007, when students had face-to-face lectures, and 2008 and 2009, when students had online recorded lectures. The results showed no significant differences for embryology results in the summative exams for the first two units over the three years. However, the results for the third unit showed a significant difference for the embryology questions over the three years. The examination scores for the bottom quartile were analysed over the three years and no differences were found that could be linked to teaching methods. Student feedback on the use of the online embryology lectures was assessed using a six-point Likert-type survey administered to students at the end of the course. In general, the participating students favoured face-to-face lectures. Positive comments about using the online embryology lectures included that it allowed students to watch the lecture many times, it helped them to visualise complex structures and concepts, and students could pause and rewind the lectures. In contrast, students mentioned some weaknesses, including a preference for live lectures that allowed them to interact and ask questions.

The use of cloud-based education software in embryology learning

A study by (Al-Neklawy, 2017) focused on evaluating the online teaching of embryology using the WizIQ learning management system. WizIQ is a cloud-based education platform that allows the user to create a virtual classroom with different student capacities, where the students can access teaching and training modules through smartphones and laptops. The course was 12 hours in duration, divided into two lectures each week for three weeks. The major course topics were introduction to embryology, gametogenesis, and female reproductive cycles. The information in the lectures was covered using simple methods, including coloured illustrations, real images, and animations. Attending the virtual classroom was voluntary and the participating students did not have to register. An invitation to attend the virtual classroom was sent to 100 first-year medical students. At the end of the course, the participating students were asked to complete an online survey to assess their perceptions of the virtual classroom with regard to delivery instructions, creating a useful learning environment, and administration issues. The students were also asked to compare the virtual classroom with face-to-face learning and to provide their insights into how to improve the course. The results showed that the majority of students positively perceived the benefits of the instructional method used in the course and the majority strongly liked the virtual classroom design and format. The majority of students strongly agreed that the virtual classroom supported student learning and supported recording the course materials and making them available to students. Of the participating students, 46% found that the virtual online classroom was the same as face-to-face learning and 35% found that the online classroom was better than the face-to-face classroom.

Videos for embryology teaching

The benefits of using videos of embryology processes on student understanding and learning of embryology was investigated (Koscinski et al., 2019). The study was divided into two steps. In the first step, three short videos on pre-implantation embryo development were presented to students in a medical ethics lecture. After three months, the participating students were asked to complete a satisfaction Likert-type survey that covered student interests, comprehension, and memorisation. In the second step, videos were introduced into embryology lectures. At the end of the course, students completed an embryology exam that covered all of the embryology course material and was not restricted to the video content. The test results were compared to embryology course test results from the preceding five years. The results for step 1 showed that a total of 190 students completed the survey (including 59 students who repeated the year). Of these, 90.6% found that the videos contributed to a better understanding of embryology, while 78.4% found that the videos helped in memorisation of embryo development. The majority of students found that the videos increased their interest in learning embryology. With regards to step 2, the results showed that correct answers for questions related to the video content had a high mean rate of 30%, compared to questions not related to the video content, which had a mean rate of 9%.

4.4.5 Synthesis

The results of the two studies (short-term, long-term) in (Marsh et al., 2008) showed that animated materials are more useful when students become familiar with them. The long-term study found that students who used the animated materials had better scores, indicating this would help students with their long-term retention of the studied materials and information. That study (Marsh et al., 2008) showed that animated materials have many benefits for students learning embryology and have a positive impact on short-term and long-term student scores.

The goals of any new curriculum must take newly available teaching resources into consideration (Moraes and Pereira, 2010). The literature includes several studies that focus on evaluating new teaching resources in embryology learning (Moraes and Pereira, 2010). The participating students had good test scores, indicating that these teaching methods are useful educational resources. The new 3D techniques are useful resources that can support traditional teaching methods, including dissection, to improve student anatomy and embryology education (Abid et al., 2010). The main advantage of 3D techniques is their availability, allowing students to use them many times in their own time to review and revise and improve their understanding. The use of 3D techniques has been shown to be effective when teaching dynamic phenomena and is particularly useful for teaching embryogenesis (Abid et al., 2010). Despite the benefits of 3D techniques, traditional teaching methods that include cadaveric dissection must continue to be used until new 3D teaching methods become more efficient.

The use of new resources such as screencasts encourages students to access and download these resources to enhance their embryology learning (Evans, 2011). A decrease in the number of downloaded embryology screencasts as the module progressed may have been due to the novelty factor of this learning method wearing off (Evans, 2011). Some students accessed the embryology screencasts multiple times, indicating that either students liked the screencasts as learning resources or that the screencasts helped the students to understand difficult concepts by allowing them to go over the material many times. In the study (Evans, 2011), Wednesday was the most popular day for downloading screencasts. This may be because there were no timetabled teaching lectures or sessions on Wednesdays. The majority of students positively perceived the use of embryology screencasts as learning and review resources and as useful resources to support lecture materials. However, students found the speed of the narration was fast and that it needed to be slower to allow for better understanding. (Beale et al., 2014) compared face-to-face lectures with online recorded embryology lectures and found no effect on student performance. Students favoured interactivity with instructors in face-to-face lectures as this allowed student to clarify questions or raise concerns in class. The online recoded lectures provide flexibility for students as they could access the lecture at any time and place, and they can view the lectures many times with the option to pause and rewind.

Many of the studies showed the benefits of combining e-learning resources with traditional classroom teaching (Gallagher et al., 2005). Even though the results of Gallagher et al. (2005) showed that online learning can be an additional and beneficial teaching resource, there is not enough evidence to suggest that it can replace traditional teaching methods (Al-Neklawy, 2017). Online learning and face-to-face teaching methods can be used together to enhance student learning of embryology and anatomy in what is defined as blended learning (Al-Neklawy, 2017). Blended learning provides students with the advantages of accessing resources anytime and anywhere, especially if the resources are interactive, and they allow students to review the material many times to enhance their performance (Makhdoom et al., 2013). In addition, blended learning will reduce the isolation felt by some students when only using online resources (Hara, 2000; Wu et al., 2010).

The introduction of embryology teaching methods that connect learning concepts with real clinical cases serves to increase student interest in learning embryology (Koscinski et al., 2019). The benefits of using videos over static pictures reduces the time that students need to understand the relationships between different structures, and it also helps with memorisation (Koscinski et al., 2019). The use of videos to teach embryology can motivate students but, based on the test results, it is not guaranteed to improve student performance or long-term memory (Koscinski et al., 2019).

4.4.6 Conclusion

The main aim of the present systematic review was to review the most recent studies and research on the topic of embryology teaching resources and to evaluate their effectiveness. The main conclusions from the review are that there is evidence to suggest that students require extra support when learning embryology and that using different resources to teach embryology enhances student performance and understanding. The majority of the reviewed studies evaluated student satisfaction and perception when using new resources, revealing positive perceptions from the participating students toward the use of these new resources, including videos, screencasts, web-page animations, and interactive software.

4.5 Limitations

This limitation section covers all the limitations from the three systematic reviews that were conducted in this study. Even though the systematic reviews followed all the guidelines and approaches for conducting a systematic review, they had some limitations. First, we used only one database, PubMed, and therefore some studies covering our objectives and aims and included in other databases may have been excluded from our review. The use of other databases, such as Google Scholar, resulted in a large number of articles and studies not being screened or checked in the time given to complete the systematic reviews. In addition, only articles written in English were included in this review.

Chapter 5. Methods

5.1 Theoretical Stance and Approach

The study research questions (**section 3.2**) can be addressed primarily with a post-positivist epistemological stance, where the extent of learning gains and student perceptions can be measured through the collection of both numerical and textual data, with subsequent analysis performed using quantitative and semi-quantitative approaches (Tavakol and Sandars, 2014a). However, the goals and research questions of this study also make it necessary to take an interpretivist approach to the collection of rich qualitative data, in order to triangulate the findings through deep exploration of how and why certain 3D learning approaches impact student learning (Tavakol and Sandars, 2014a). Therefore, an overall pragmatic approach (Yvonne Feilzer, 2010; van Griensven et al., 2014; Cohen et al., 2018c; Taguchi, 2018) must be taken to this research to ensure that the entire scope of the research aim can be satisfied.

5.2 Educational Context

The undergraduate Bachelor of Medicine and Surgery (MBBS) degree is a five-year programme delivered by the Medical School at Newcastle University (MSNU), UK. The programme has an integrated case-led curriculum that provides students with early essential clinical experience. The medical programme has certain pre-admission criteria based on applicant grades in further education, such as advanced level (A-level) qualifications for UK applicants or an International Baccalaureate or equivalent for international applicants. In addition, applicants must pass the United Kingdom Clinical Aptitude Test (UKCAT) and perform well at interview. Graduating students are qualified to practice medicine in the United Kingdom, and following a two-year foundation position, they can apply for professional post-graduate training. First-year (Stage 1) MBBS students are typically 18 years old when they start the programme, with a ratio of 50/50 males to females. A curriculum review resulted in the design and implementation of a new MBBS curriculum, which launched in 2017. Here, the previous and current iterations are therefore referred to as the 'pre-2017' and 'post-2017' curriculum, respectively. Students graduated with a basic understanding of the clinical and medical sciences and the main principles of clinical practice. This is the major outcome and focus of the medical degree programme.

5.2.1 Anatomy delivery at Newcastle University within the pre-2017 UK medical curriculum

The pre-2017 medical degree programme consisted of two phases. Phase I included lectures and practical sessions and it is delivered over two years (Stage 1 and Stage 2). Pre-2017 phase I cohorts typically varied between 200–250 students. Phase II consisted of clinical placements for students in Stage 3 and Stage 5 and includes problem-based learning and lectures. Approximately 48 sequentially combined clinical case studies were delivered in Phase I. Compulsory study units were delivered in specific areas, including cardiovascular, renal, abdominal, and respiratory medicine, and metabolism and nutrition. Anatomy education and teaching were delivered as a combined clinical and regional approach. Anatomy was taught and presented only in Phase I of the medical degree programme through formal whole-cohort that includes lectures and practical sessions. The practical sessions were delivered in the Anatomy and Clinical Skills DR at the Medical School at Newcastle University. At the start of the academic year, the entire cohort was randomly divided into 12 subgroups for anatomy practical sessions and seminars.

In addition, practical sessions were delivered twice to half of the cohort, each of which consisted of six subgroups. Each subgroup would occupy one bay in the DR. In each practical session, each sub-group was assisted by an academic staff member or an anatomy demonstrator (1:18 staff: student ratio), who was at that time a Foundation Year 2 (FY2) junior doctor. Each student received around fifty hours of anatomy lectures and 60 hours of anatomy practical sessions delivered by 5 core academic staff members. The teaching hours were divided between 8 units of study in Phase I.

Each session had unique learning outcomes with specific knowledge and skills, on which the students were formatively assessed in single-best answer examinations. Resources, including plastic models, prosected cadaveric specimens and clinical images software, mainly Virtual Human Dissector (VHD), were used in the DR. Self-study resources, such as online interactive tutorials and online resources, are offered to the students to support anatomy learning rather than to teach or deliver anatomy content to meet Phase I learning outcomes. Pre-2017, the self-directed learning resources were accessed using the Learning Support Environment (LSE) which was the earlier version of the MLE.

At Stage 4, a small number of students in selected component (SSC) projects were able to undertake dissection of a part in a particular region. In addition to MBBS students, the

Anatomy and Clinical Skills Centre at Newcastle University delivered anatomy teaching to Dental Surgery and Biomedical Sciences degree programme students prior to 2017

5.2.2 Anatomy delivery at Newcastle University within the post-2017 UK medical curriculum

An integrated case-based format was implemented for the first time in the five-year MBBS (Bachelor of Medicine and Surgery) medical programme at Newcastle University in the post-2017 curriculum. First year MBBS students in the academic year 2017/2018 were the first group to take integrated case-based format modules.

Since the introduction of the new post-2017 curriculum, the number of enrolled students has increased. In the academic year 2017/2018, the entry cohort comprised 287 students, and in the academic year 2018/2019, this increased to 335 students.

During the first two pre-clinical years of the programme, 25 distinct cases are taught within the *Essentials of Medical Practice* (EOMP) component.

Each case is one to four weeks in length. The first three weeks are an introductory foundation unit in the first year, followed by three weeks '*Transition to Clinically-Based Learning'* unit by the end of the second year. Anatomy is only taught and embedded in the '*Essentials of Medical Practice'* phase, with related cases during the course of the first year and second year. For example, anatomy teaching in the academic year 2018/2019 was included in the first-year Case 1 (heart disease), embedded in cardiovascular and thoracic anatomy, and in Case 2 (kidney disease), the abdominal and the renal anatomy were included.

With the exception of a short period of suspension of in-person teaching during the Covid-19 pandemic (March 2020–January 2021), EOMP anatomy is implemented and delivered in lecture-based practical sessions in the DR, using plastic models, 3DP models, and self-directed online learning resources.

The anatomy practical sessions are delivered in sessions of 1–1.5 hours in duration. These practical sessions are repeated almost eight times per cohort to include groups of almost 40 students in each session, who were then distributed into five or six subgroups. Each subgroup comprises approximately eight students assisted by an anatomical staff member or an academic or surgical trainee demonstrator in a separate laboratory bay.

An advantage of the post-2017 curriculum is that the anatomy practical sessions are delivered to smaller groups of eight students, compared to a large group of 18 students per laboratory bay in the pre-2017 curriculum (**Section 5.2.1**). However, the total contact time for each first-and second-year student in the anatomy laboratory was 28 hours in the post-2017 curriculum, compared to 57 hours in the current pre-2017 curriculum (Ben Awadh et al., 2022).

Anatomy practical sessions in the post-2017 curriculum are facilitated by the use of plastic models, 3DP models, digital resources, prosection, and self-directed learning resources (Keenan and ben Awadh, 2019a; Keenan and Powell, 2020; Ben Awadh et al., 2022).

Anatomy delivery within the Physician Associate Studies programme at Newcastle University

The physician associate (PA) students in the academic year of 2018/2019 participated in part of the study. The Physician Associates Studies at Newcastle University is a 24 months full-time programme with off-campus clinical rotations and placements within Northeast hospitals and primary care settings that is designed for graduates of a bioscience discipline. The program delivers bioscience courses intended to deliver excellent medial training. In the beginning of the programme, the students are taught the Anatomical Basis of Clinical Examination that Includes gross anatomy, imaging, and surface anatomy as part of a foundation unit of study comprising an introduction to clinical and communication skills in a case-based form that is very similar to the MBBS. PA students had 9 hours of anatomy learning that involved lectures and practical session in the DR in which the thorax, the abdomen, and the lower limbs were covered.

5.2.3 Pandemic-era anatomy delivery at Newcastle University

As of March 2020, COVID-19 was considered to be a high-risk infectious disease in the UK. The university followed the government guidelines by announcing significant new measures designed to reduce the spread of the virus. On 17 March 2020, the university stopped all face-to-face classes and suspended all non-essential work in all of its research environments until such time as the government and the central university lifted restrictions. My research, which involved direct interaction with students by introducing new methods to improve anatomy education, was affected by these new COVID-19 measures. The need to rapidly transition to remote learning became necessary as an alternative to traditional teaching methods. The rapidly changing situation was also problematic with regard to changes to the delivery of the medical curriculum which, therefore, impacted the research design, the delivery of resources, and the working environment.

Three different anatomy teaching strategies were implemented depending on the development of the pandemic and subsequent university regulations. During the first stage, in March 2020, there was no anatomy teaching as most of the anatomy lectures and materials had already been presented before the COVID-19 outbreak. During the second stage, which started in the first term of the academic year 2020/2021, there was no contact teaching, and core anatomy learning for undergraduate medicine consisted of pre-recorded lectures and tutorials combined with integrated asynchronous remote resources on the MLE. In addition, Zoom webinars were introduced with a focus on using Complete Anatomy software (Elsevier, Amsterdam, Netherlands) (Motsinger, 2020). SEP learning activities and Digital Embryology Resources learning activities were also designed for tutorial use and were embedded within the MLE. The rapid changes to teaching methods were taken into consideration as students were likely to experience anxiety due to the pandemic and the rapidly changing education and assessment situation. During stage three, which started in the second term of the academic year 2020/2021, contact teaching resumed in adherence with social distancing guidelines. Practical sessions in the DR were replaced with live streaming from the DR to demonstrate anatomy structures using plastic models only. In the academic year 2021/2022, anatomy teaching returned to normal, as discussed in **Section 5.2.2**, with protective personal equipment (PPE) precautions, but without social distancing precautions.

5.3 Project Methods

5.3.1 Recruitment and sampling

Undergraduate students in the Medical School at Newcastle University (MSNU) were recruited for research as required. The research project was publicised through one or more of the following routes depending on specific degree programme regulations: practical teaching sessions, lectures, social media, and via email (only during COVID-19 Pandemic). Before sampling, a power calculation was conducted to identify the minimum sample size required for the study; this step was only carried out for the post-positivist elements of the study (Jones et al., 2003). In addition, for the post-positivist experimental and survey methodologies, the required sample size was calculated based on a 95% confidence level (CL) and a 5% confidence interval (CI) for the data (Cohen et al., 2018e; Campbell, 2021a). A 95% CL indicates that the researcher is 95% confident about the result and that results cover 95% of the core distribution (Cohen et al., 2018e). As the mean medical student cohort for each stage was 330 students, the targeted sample size was calculated using an online calculator (Raosoft, 2004); the sample size should be 178 students to achieve a 95% CL with a 5% Cl.

5.3.2 Evaluation of approaches within teaching sessions or within self-directed online learning resources

Optional or timetabled practical sessions and online self-directed learning resources were utilised for the research. Specific novel learning approaches could be evaluated during lectures, seminars, practical sessions, and self-directed online learning scenarios. Curriculum learning outcomes were delivered in all sessions as required so that students were not disadvantaged by the research. The sessions involved teaching topics in gross anatomy or embryology using standard methods such as cadavers and prosection specimens, or other appropriate control activities compared to our intervention that consisted of new technology, such as Sectra, 3DP models, and digital embryology resources. All students had the opportunity to use both standard methods and the intervention to satisfy the relevant curricular learning outcomes.

5.3.3 Experimental studies

Pre-post and delayed knowledge and skills testing

Pre-tests were designed and implemented to identify baseline knowledge, skills, understanding, and retention of participants. Moreover, experimental approaches were produced to identify spatial ability and understanding of the 3D aspects of anatomy structures. The tests were written and the participants completed the test prior to each teaching session or use of an online resource. After the practical session, an immediate post-test was administered. This was either a written or practical evaluation of the extent of learning using standard methods compared with the intervention. A delayed test was implemented to identify participant long-term memory recall and knowledge retention.

MR test

Spatial abilities and MR are important skills for medical students (Jamil et al., 2019). Spatial ability is defined as "*the ability to generate, retrieve, retain, and transform the data into visual images*" (Lohman, 1996). MR is the skill and the ability to create mental images of 3D or 2D objects and to be able to mentally turn the object in space and visualise all aspects of the object (Carroll, 1993; Hoyek et al., 2009). To measure students' spatial and MR abilities and to investigate the relationship between MR scores and learning performance when using 3D multimodal resources, a modified MR test (MRT) was created based on previous work (Vandenberg and Kuse, 1978; Peters et al., 1995; Guillot et al., 2007). An example of the test is provided in **Figure 5.1**. The MRT was administered with all the instructions to first year medical students (**Table 5.3**) early in the academic year 2018/2019 prior to any anatomy teaching. The MRT contains 10 problem sets of geometric shapes. Each set consists of one model and four alternative options. Participants were asked to choose the two correct images from four images that represented the correct rotation of each original shape, scoring one point per correct shape. Each participant received a final score in the range 0–20. Learners had five minutes to answer the 10 problems and submit the test.

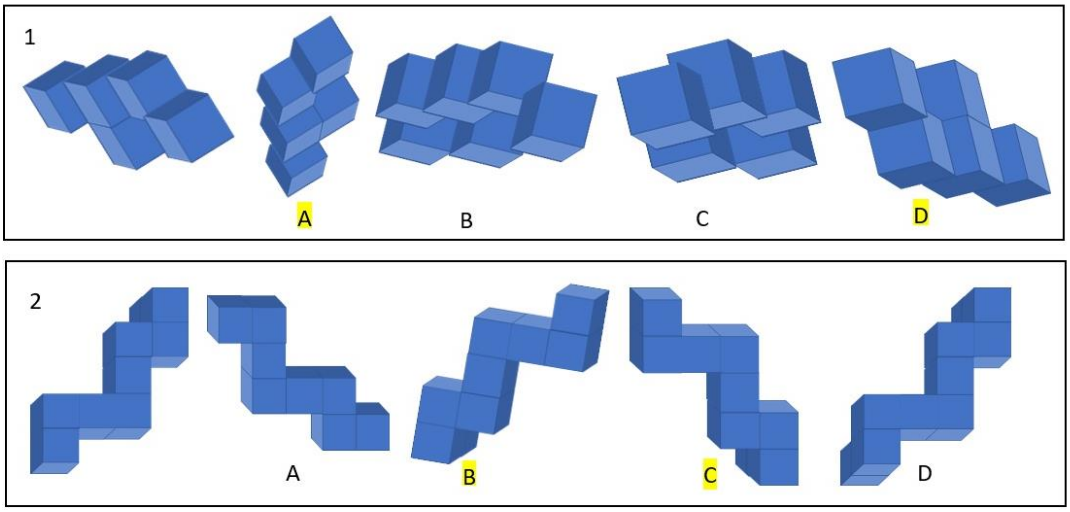


Figure 5.1: Items from the MRT
The correct answers are highlighted by yellow marker.

5.3.4 Survey-based studies

Post-positivist survey methodologies were utilised to address the enquiry goals, providing coherence within the pragmatic paradigm of the research (Cohen et al., 2018a). The survey is a descriptive methodology (non-experimental methodology) that is used to describe the existing characteristics of the participants (Turner et al., 2013). The quality of the survey depends on the response rate, and the survey can measure the attitudes, knowledge, preferences and concerns of the participants (Turner et al., 2013). The survey is an effective methodology to collect data at certain points in time to describe the nature of certain conditions (Cohen et al., 2018f). The survey is coherent with a post-positivist paradigm. A questionnaire is the method most frequently used in medical education research to collect quantitative survey data (Tavakol and Sandars, 2014b). In the project, multiple questionnaire questions that included gender, age, and academic degree were designed, validated, and piloted to obtain insights regarding demographics, learning approaches, and participant preferences and how these factors might influence 3D anatomy learning and understanding. Participant perceptions were measured using a Likert-type scale questionnaire, and a deeper exploration of perspectives was sought using specifically designed free-text questionnaire items. In this project, all the questionnaire designs were based on previous work (Leung, 2011; Magee et al., 2013; Sullivan and Artino, 2013; Artino et al., 2014; Backhouse et al., 2017) and modified to reflect the aims of this project. Likert-type questionnaires are widely used in medical education studies and research (Sullivan and Artino, 2013; Artino et al., 2014). The advantages of the questionnaire include facilitating the collection of data from a large number of participants, the ability to generate numerical data, the ability to support or reject research assumptions, the ability to make generalisations about a large population, and to provide assistance in understating a phenomenon or behaviour (Allery, 2016; Cohen et al., 2018f). In medical education in particular, the questionnaire is an effective method to evaluate a course or a curriculum, or to obtain feedback about participant teaching and learning experiences (Woodward, 1988). The Likert scale questionnaire was first developed in 1932 by Rensis Likert to measure attitudes (Likert, 1932; Sullivan and Artino, 2013). Since then, the Likert-type questionnaire has become one of the most popular methods used to determine perceptions, attitudes, and opinions (Leung, 2011; Sullivan and Artino, 2013). The most common Likert-type scale is a five-point or seven-point ordinal scale applied by the participants to rate a specific questionnaire item (Carifio and Perla, 2008; Sullivan and Artino, 2013; Allery, 2016). In this project, a seven-point Likert-type scale was selected because it is more accurate and it provides a more effective reflection of respondent perceptions than a five-point scale (Finstad, 2010). The steps in designing the questionnaire items matched those of previous studies (Magee et al., 2013; Artino et al., 2014; Allery, 2016) to ensure that the questionnaire measures the intended outcomes (**Table 5.1**). The designed questionnaire was checked to ensure that it would translate the research aims and objectives. Finally, the questionnaire was checked to make sure that it did not contain any ambiguous questions, statements, or instructions and that it would motivate the participants to answer. Two of the four questionnaires used in this project were redesigned based on the results of pilot studies. In addition, the reliability of the questionnaire was confirmed by measuring the internal consistency of questionnaire items using Cronbach's alpha, where the acceptable range was 0.7–0.90 (Tavakol and Dennick, 2011). To gain more information from the students, free-text questions were included in the questionnaires. The design of the free-text questions was built on prior work by (Backhouse et al., 2017). Pilot testing and collaboration between the supervisor (Dr Iain Keenan) and the PhD candidate (Abdullah ben Awadh) were performed to design and improve the free-text questions.

	Steps	**Description**
1	The intent of the questionnaire	Setting the aim of the questionnaire results and how they will contribute to the study.
2	Content and research background	To check if the same content already exists and to check the ability to adapt an existing questionnaire. To ensure that the questionnaire is coherent with previous studies or theories.
3	Know the type of questions	Four types of questions used in most questionnaires to measure attitudes, beliefs, behaviours, attributes.
4	Develop items	The questionnaire items should be simply worded to avoid confusion and misunderstanding. The questions should be clear and as specific as possible. The questions should be applicable to all respondents to avoid misleading results.
5	Expert validation	To evaluate the clarity of the questionnaire items and ensure the items are relevant to the intended participants.
6	Interview	Interview with a potential participant to ensure that the items are clear and to ensure that the participants interpret the questions as intended.
7	Pilot testing	To check the validity and reliability of the questionnaire and to check the adequacy of the questionnaire items.

Table 5.1: An overview of the framework used in this project to construct and design questionnaires.
The table explains in detail the steps taken in the project to design questionnaires, and the information collected from a previous study (Artino et al., 2014).

5.3.5 Phenomenological studies

Phenomenology is a methodology that is coherent with an interpretivist approach (Mackey, 2005). The approach is used to describe and understand a phenomenon by investigating and exploring the preservative and opinions of those who experienced that phenomenon (Holloway and Todres, 2003; Teherani et al., 2015). The focus is to understand how individuals make sense of their lived experience and how it is transformed into consciousness (Turner et al., 2013). It is important to illustrate that the research question (Refer back to RQ 3) should be carefully designed to understand the meaning of the phenomenon and the lived experiences of the participants (Turner et al., 2013; Teherani et al., 2015). A focus group is one of the methods used to gather data from the participants to understand and describe the phenomena of interest based on their lived experience (Randles, 2012). A focus group is a method that is commonly used in qualitative research (Randles, 2012; Stalmeijer et al., 2014) A focus group is a group discussion used to explore or investigate specific issues. Focus groups are used to evaluate programmes, to collect qualitative data, and to validate questionnaires (Stalmeijer et al., 2014; Krueger, 2015). Three to four focus groups are usually ideal for data collection (Stalmeijer et al., 2014; Krueger, 2015). The number of groups can be increased until saturation is reached. Saturation means the use of many groups until the research questions are answered or new groups have no new information to add to the collected data. Depending on the type and purpose of the study, the number of participants in a focus group will vary. Some resources suggest that the acceptable number of participants per group is 6–10 (Stalmeijer et al., 2014), 4–14 (Then et al., 2014) or 5–8 (Krueger and Casey, 2015). Recently, 4–6 participants per group has become more popular because small groups allow more interaction between participants, and they provide logistical advantages for recruitment and hosting (Krueger, 2015).

Here, focus group discussions were audio recorded using an iPad and smart phone. A written design for the discussion and the questions was prepared before the discussion session. Each recorded focus group session was then transcribed verbatim, and the data were analysed using thematic analysis (Braun and Clarke, 2006; Maguire and Delahunt, 2017; Shapiro et al., 2020). Several focus group sessions were conducted to investigate challenging anatomy topics that the students faced, to identify the most effective teaching and self-directed learning resources, and to investigate the effects of COVID-19 on anatomy teaching.

5.3.6 Statistical analysis of quantitative data

Choosing appropriate statistical tests is an important step to ensuring the quality and validity of results. The first step in choosing an appropriate statistical test is identifying the type of the data, such as interval or ordinal data (McCrum-Gardner, 2008). The second step involves performing a normality test to check if the data have a parametric or non-parametric distribution (**Figure 5.2**). Two very commonly used statistical tests of normality are the Shapiro-Wilk Test and the Kolmogorov-Smirnoff Test (Yazici and Yolacan, 2007; Razali and Wah, 2011; Das and Imon, 2016). After performing the normality tests, the Likert-type data obtained from the questionnaire were indicated as non-parametric. After identifying the type of data, the appropriate test could be chosen. Here, the Friedman test and a pairwise comparison were performed to identify the statistical significance of three or more questionnaire items. The Friedman test is a non-parametric test equivalent to the repeated ANOVA measures used for parametric data (Sheldon et al., 1996; Peat and Barton, 2008; Ennos and Johnson, 2012). To compare two questionnaire items, the non-parametric test equivalent to and the same as the paired t-test is the Wilcoxon signed-rank test (Peat and Barton, 2008; Harris and Hardin, 2013). The normality tests, Friedman test, and Wilcoxon signed-rank test were all performed using SPSS version 27.0 (SPSS, Chicago, IL, USA).

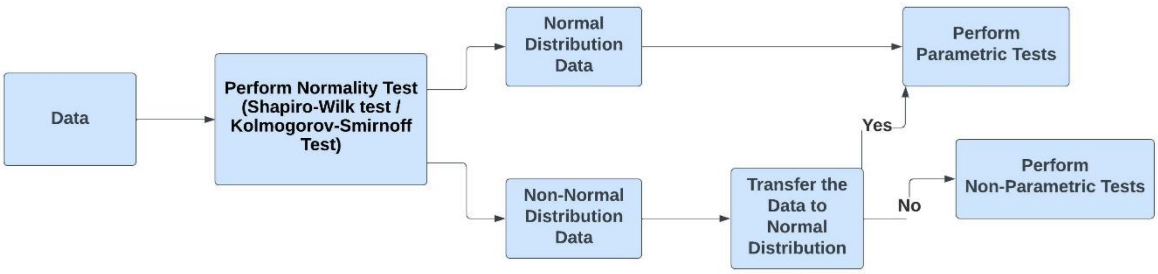


Figure 5.2: Summary of the steps used to choose the appropriate statistical tests.
The figure is modified from (Peat and Barton, 2008).

5.3.7 Regression analysis

A regression analysis was performed to identify the relationship between MRT test scores and student performance when utilising 3D multimodal resources. The relationship could be identified by the boundaries of correlation. Boundaries were defined in advance from weak correlation to strong correlation in relation to these values, in which R^2 = 0.8−1 indicates a very strong correlation; R^2 = 0.6−0.79 indicates a strong correlation; R^2= 0.4−0.59 indicates a moderate correlation; R^2 = 0.2−0.39 indicates a weak correlation; and R^2 = 0−0.19 indicates a very weak correlation (Campbell, 2021b).

5.3.8 Semi-quantitative thematic content analysis

To ensure coherence with the post-positivist theoretical stance of the survey methodology, semi-quantitative thematic content analysis was conducted to analyse free-text questionnaire items. A semi-quantitative thematic content analysis approach is based on counting the occurrence and the frequency of themes that arise during the analysis. It is used in order to provide an objective and logical analysis of the materials (Franzosi, 2008). The first step in semi-quantitative thematic content analysis involved identifying the codes into themes and, to increase rigour, a blind double-coding approach was applied to this content analysis of the free-text questionnaire questions. In our project, a blind double-coded analysis was independently performed and reviewed by Dr Iain Keenan (supervisor) and Abdullah ben Awadh (PhD candidate) to explore broader themes and to ensure the coherence of the themes arising from learner responses. These themes were then combined to identify the final themes approved and agreed upon by both researchers. Counting the frequency of themes arising from free-text items provided an overview and objective analysis of the materials content (Franzosi, 2008; Vaismoradi et al., 2013; Backhouse et al., 2017). The percentage of participants who responded under each theme was then calculated from the total number of students (Webb and Choi, 2014; Backhouse et al., 2017).

5.3.9 Qualitative thematic analysis

To ensure coherence with the interpretivist theoretical stance of the phenomenological methodology used, a qualitative thematic analysis was performed on the focus group data. Thematic analysis is a qualitative method used widely in psychology and the social sciences (Braun and Clarke, 2006; Maguire and Delahunt, 2017). It is a method that analyses and identifies themes and patterns within the data (Braun and Clarke, 2006; Clarke and Braun, 2013; Maguire and Delahunt, 2017). One of the advantages of thematic analysis is that it is a useful and flexible tool that can be used to provide detailed and complex information about the data (Braun and Clarke, 2006). In our project, thematic analysis was considered essentialist or realist in which the analysis recorded and reported the reality of participants' experiences. The theme is an important point that reveals important information about the data in relation to the research questions, emphasising patterns or meaning in the data. In our project, we followed Braun and Clarke’s (2006) six-phase framework of thematic analysis. The six-phase framework was adopted for the following reasons:

- It is considered to be the most influential approach (Maguire and Delahunt, 2017);
- It offers a clear and useful step-by-step framework for performing thematic analysis.

Before undertaking the analysis, we needed to understand the difference between the two levels of themes – the semantic and the latent. Semantic themes focus on analysing the surface meaning of the data and do not explore beyond what the participant has written or said (Braun and Clarke, 2006; Maguire and Delahunt, 2017). The semantic level is appropriate for representing learning and teaching work, which was the aim of our project. In comparison, latent themes go beyond the semantic content of the data by identifying or examining underlying ideas, beliefs, and conceptualisations of the main idea. It is theorized that these are the semantic contents of the data (Braun and Clarke, 2006). Braun and Clarke’s six phases for conducting a successful thematic analysis are summarised in **Table 5.2.**

Phase	Description
1. Be familiar with the data	The transcript should be read many times to gain familiarity with the data. In this step, you need to be familiar with the focus group transcripts and make notes with initial ideas.
2. Initial code generation	Organizing the data into systematic and meaningful codes across the whole dataset. Coding is the process of breaking down the data into smaller segments and collating the information relevant to each code.
3. Searching for themes	Adding all the generated codes into possible themes or wider topics that can include all the codes by adding all the data relevant to each possible theme.
4. Reviewing the themes	In this step, it is important to check if the generated themes are related to the extracted codes and to the entire data set. This involves generating a thematic map of the investigated themes and codes to create an overview of the analysis. The themes should be different from each other.
5. Naming and defining the themes	Generating the final names and definitions of the themes after constant analysis and review to improve each theme so that it is coherent with the full story of the analysis.
6. Writing the report	A final analysis of the data should be performed to ensure the validity of the themes. Writing a report of the analysis by relating it back to the research questions.

Table 5.2: Summary of Braun and Clarke's (Braun and Clarke, 2006) six-phase framework for conducting a thematic analysis.

The table explains in detail the steps followed in this project to perform a thematic analysis of the focus group data based on the six-phase framework of Braun and Clarke (2006).

5.3.10 Research phases

For the purposes of addressing each research question, the project was divided into four distinct phases:

Phase I (2017/2018) involved investigating learner perceptions of challenging topics and areas when studying anatomy to address the first research question. Second-year medical students (2MBBS) were chosen for this part of the research to provide their perceptions of challenging anatomy topics because, by semester 2 of academic year 2017/18, they had completed all of the anatomy content delivered in the pre-2017 MBBS programme. The students also provided their insights about the benefits of using the Sectra table, having used the table during practical anatomy sessions in semester 1 of their second year (2017/18).

Phase II (2018/2019) involved investigating the added values of in-person resources for 3D gross anatomy and 2D clinical imaging through the implementation of the Sectra VT and 3DP model learning activities during practical sessions for PA pilot study and for first-year medical students (1MBBS). Student feedback and perceptions were collected via questionnaires and focus groups and performance was measured through experimental testing. All the following phases were designed to address the second and third research questions.

Phase III (2019/2020) included an investigation of the benefits of remote and asynchronous resources for gross anatomy and 2D clinical imaging through the implementation and evaluation of self-directed learning approaches involving 3DP models and the SEP. Student insights about the use of the SEP were collected via questionnaires and focus groups and performance enhancement was measured by experimental testing.

Phase IV (2020) was the final phase of the research, which involved the implementation of remote and asynchronous resources (digital embryology resources, Human Development Biology Resource (HDBR) digital heart models, and interactive PDFs) for embryology learning. The benefits of their use in improving students' understanding of embryology topics were evaluated via questionnaires and focus groups.

5.4 Steps to Ensure Methodological Rigour

5.4.1 Learning activities for Phase I

The second-year medical students in the academic year 2017/2018 were still part of the pre-2017 curriculum. In the pre-2017 curriculum, all anatomy teaching was completed by the end of semester 1 of Year 2, in which students completed lectures and practical session on the head and neck, neuroanatomy, upper limbs, and lower limbs. In Year 1 they had learned about the thorax, pelvis, and abdomen.

5.4.2 Learning activities for Phase II and Phase III

The materials and delivery of the learning activities, tests, and assessments included in this study were planed and designed to make sure that the data were comparable, and that they provided a basic introduction to the interpretation of the thoracic and abdominal sections of the anatomy curriculum using cross-sectional images.

In Phase II (Sectra + 3DP models (intervention), 2D images (control)) and Phase III (Sectra + 3DP models (control), SEP (intervention)), the participants were allocated to 10-minute learning activities within 90-minute practical sessions with a demonstrator. This ensured that all students in both the control and the intervention groups spent the same time on the task to ensure equivalence of the same context for both activities.

Confusing variables were eliminated between the control and intervention activities as far as possible. To ensure that the participants in the entire first year medical cohort (n = 335) had the same chance to participate in both the intervention and the control activities in both phases, the learning activities were repeated 40 times and in each practical session the students were divided into five groups with approximately eight students per group (n = 8).

In **Phase II**, all the groups participated in the thoracic learning activities with the Sectra + 3DP models used as an intervention. In the same phase, all the groups participated in abdominal learning activities with the use of 2D images as a control. In this case, all of the first-year medical student cohort had the opportunity to participate in both intervention and control activities. In **Phase III**, the learning activities and the group divisions (each activity was repeated 40 times, for five student sub-groups per practical session (n = 8 students per sub-group) and for each of all eight repeats of every practical session (n = 40 students per group) so that every first-year medical student (n = 335) experienced the activity. Similar to Phase II, in which all the participating students had an equal opportunity to participate in the intervention activity in the abdomen case with the implementation of the SEP and in the control activities in the thorax case with the use of Sectra + 3DP models.

All of the demonstrators and leads of both activities were well trained and provided with detailed instruction guides to ensure consistency of activities. The aim throughout this study was to maintain consistency in the delivery of anatomy materials and content in both the intervention and the control activities in Phase II and Phase III by concentrating on the same primary anatomical structures and regions in each case. In addition, the control and intervention activities involved the same task sheets for interpretation of prominent anatomical structures and features, including the major blood vessels and the viscera in cross sectional clinical images.

Sectra + 3DP models were used in the thoracic case, which was the intervention in Phase II and the control in Phase III. All students were required to interpret the size, shape, position, and appearance of the major structures of the cardiovascular system, including the descending and ascending aorta, aortic arch, superior and inferior venae cavae, and the heart chambers, in addition to notable related structures such as the trachea and lungs. In the control activity, students were required to identify and interpret the important features of the abdomen, such as the lobes of the liver, pancreas, oesophagus, kidneys, spleen, and abdominal aorta on cross-sectional images. Later studies followed this format, but with the following alterations: in the Phase II abdominal case, 2D images were used as the control. In Phase III, the SEP was used as the intervention.

5.4.3 Experimental testing

Power calculations identified that a sample (n = 179) of the total cohort (n = 335) was required for a CL of 95% to achieve and obtain strong quantitative results.

The pre- and post-test questions in Phases II and III were designed to be adequately different to ensure that the pre-test answers did not affect students' responses in the post-test and to avoid students focusing on items that were shown in the pre-test (Ben Awadh et al., 2022). The difficulty levels of the pre-test and post-test questions were similar and the anatomical features that students were required to distinguish and identify were as comparable as possible between the pre-test and post-test, and between the intervention activities and the control activities. In both the pre-test and the post-test for both the intervention and the control for Phase II and Phase III, students were asked to distinguish and identify major visceral organs and prominent vascular structures on cross-sectional images (**Appendix**).

Following this approach ensured that the anatomical structures delivered in each learning activity were similar with those shown in the experimental testing.

Moreover, the same number of CT scans, virtual human dissection image formats and radiographs were included in each test to provide consistency and similarity in the imaging modalities used in the intervention and control activities in Phase II and Phase III (Ben Awadh et al., 2022). To avoid crosstalk or foreknowledge bias, the information was simultaneously provided to all the participating students by the demonstrators (Edlund et al., 2009). During and after the tests, the participants were advised not to discuss or mention their test answers with their classmates in order to reduce cross-talking, to maintain blindness, and to reduce bias (Lim et al., 2016). The content of the clinical images in each practical session was delivered only during the intervention and the control activities in Phase II and Phase III to eliminate contamination from other imaging learning activities that might affect the test scores.

5.4.4 Questionnaire instrument and validity

This project included four questionnaire designs, one for each phase. The first questionnaire designed for Phase I was in the form of a seven-point Likert-type and free-text questionnaire created based on previous work (Leung, 2011; Sullivan and Artino, 2013; Backhouse et al., 2017). After designing the questionnaire, an important step was validation to ensure that the questionnaire would provide useful data. A pilot study was performed to validate the items in the questionnaire through correlation analysis, as describe earlier. Seventeen students at MSNU participated in the pilot study. The internal consistency of the items was calculated using Cronbach's alpha, resulting in a value of 0.9, which is within the acceptable range of 0.7–0.9 (Tavakol and Dennick, 2011). This indicated that the items in the questionnaire were related and could be used in the larger-scale study. To increase the rigor of the open-text items, a blind double-coding approach to semi-quantitative thematic content analysis was performed. The same steps were followed to design and ensure the validity of the questionnaires in each of the other phases.

5.5 Phase I Methods: Challenging Topics

5.5.1 Pilot study

To validate the challenging topics questionnaire, a pilot study was conducted in January 2018 (n = 17). Three cohorts of undergraduate second-year medical students, second-year accelerated medical students and fourth-year medical students participated in the pilot study (**Table 5.3**). Cronbach's alpha was calculated and performed post hoc to check reliability and the internal consistency of the questionnaire items. The Cronbach's alpha result was 0.9, which is within the acceptable range (0.7–0.9) (Tavakol and Dennick, 2011).

Twelve females (71%) and five males (29%) participated in the pilot study. The pilot data were analysed and items were reviewed to expertly validate the questionnaire for the full study.

Cohort	Description	Abbreviation
Second-year medical students	Stage 2 of MBBS students at Newcastle University in the academic year 2017/2018	(2MBBS-17/18)
Second-year accelerated medical students	Accelerated MBBS at Newcastle University in the academic year 2017/2018	(2AMBBS-17/18)
Fourth-year medical students	Stage 4 of MBBS students at Newcastle University in the academic year 2017/2018	(4MBBS-17/18)
PA students	PA in the academic year 2018/2019	(PA-18/19)
First-year medical students	Stage 1 of MBBS students at Newcastle University in the academic year 2018/2019	(1MBBS-18/19)
First-year medical students (Group 1)	Stage 1 of MBBS students at Newcastle University in the academic year 2019/2020	(1MBBS-19/20)
First-year medical students (Group 2)	Stage 1 of MBBS students at Newcastle University in the academic year 2020/2021	(1MBBS-20/21)

Table 5.3: An overview of the student cohorts who participated in the full study.

5.5.2 Population recruiting and sampling

The challenging topics questionnaire was administered in the MSNU in March 2018, before Easter break. The sample consisted of stage 2 medical students (**2MBBS-17/18**) (**Table 5.3**). The total cohort (approximately n = 342) was invited to participate in this part of the study by live announcement after the anatomy lecture. Only 95 students of the total cohort completed and submitted the questionnaire. All of the participating students signed a consent form to allow the use of their data in the research. To identify background differences in the students' perceptions of the challenging topics, a census sample (Suresh et al., 2011) was conducted. This background information was collected to check that the students had similar anatomy experiences; the information could be used to check the impact of age and sex on test performance. The participating students had an approximate 50:50 male to female ratio, with 57.89% (n = 55) female and 42.11% (n = 40) male. The age distribution ranged from 17 to 28 years, with the majority aged between 17 and 20 years (n = 58, 61.1%).

5.5.3 Full study design

The challenging topics questionnaire was administered to stage 2 medical students **(2MBBS-17/18)** (**Table 5.3**). The students were invited to participate through in-person announcements by the researcher at the end of the anatomy lectures. Four announcements were made at the end of anatomy lectures towards the end of term and a proportion of 95 students of the total cohort (n = 342) completed and submitted the questionnaire. The students were given 10 minutes to answer the questionnaire items and the free-text questions. At the end of the 10 minutes, the researcher collected the questionnaires.

5.5.4 Likert- type questionnaire instruments

The final full study version of the challenging topics questionnaire was administered to second-year medical students (**2MBBS-17/18)** (**Table 5.4**) at MSNU in March 2018 immediately following a number of different lectures to ensure a large number of participants. By March, the second-year medical students had experienced and practiced all of the anatomy teaching and content in the pre-2017 medical programme curriculum (Ben Awadh et al., 2022). By that stage, these students had completed all lecture-based and practical teaching in in both gross anatomy and neuroanatomy, including head and neck, upper limbs, lower limbs, thorax, and abdomen. The students were invited to complete a seven-point Likert-type questionnaire (Leung, 2011) based on a previous design (Backhouse et al., 2017), with enhancements and modifications that were based on the results of the pilot study (**Section 5.5.1**). The Cronbach's alpha test was performed to confirm reliability and to ensure internal consistency of the questionnaire items, with 0.7–0.9 considered an acceptable range (Tavakol and Dennick, 2011). A value of 0.90 was calculated for the challenging topics questionnaire. The participating students were given 10 minutes to answer all the questions and return the questionnaire. Table 5.4 shows the Likert-type items in the questionnaire and a copy is included in the appendix.

Questionnaire item	Sub-item	Seven-point Likert-type scale range
1. "From your own experience of your current degree, how challenging has it been to learn the following anatomical topics?"	(A) Gross Anatomy (B) Embryology (C) Clinical imaging (D) Microanatomy (E) Histology	1 = not at all challenging 7 = extremely challenging
2. "From your own experience of your current degree, how challenging has it been to learn the following anatomical regions?"	(A) Abdomen (B) Thorax (C) Head and Neck (D) Pelvis and Perineum (E) Limbs	1 = not at all challenging 7 = extremely challenging
3. "From your own experience of your current degree, how challenging has it been to understand the gross anatomical structure of the following visceral organs?"	(A) Heart (B) Brain (C) Kidney (D) Liver and Gallbladder (E) Lungs (F) Gut (G) Pancreas	1 = not at all challenging 7 = extremely challenging
4. "From your own experience of your current degree, how challenging has it been to understand the anatomy of the following features?"	(A) Pericardial sac and sinuses (B) Pleural cavity and its reflections/boundaries (C) Peritoneum and its reflections/boundaries (D) Inguinal canal	1 = not at all challenging 7=extremely challenging
5. "From your own experience of your current degree, how challenging has it been to understand the anatomy of the following gross structures?"	(A) Fascia (B) Muscles and tendons	1 = not at all challenging

	(C) Bones and ligaments (D) Organs (E) Blood vessels (F) Nerves and plexuses	7=extremely challenging
6. "From your own experience of your current degree, how challenging has it been to identify the anatomy of the following anatomical features in cross-sectional images?"	(A) Muscles Compartments (B) Heart (C) Liver (D) Abdomen	1 = not at all challenging 7=extremely challenging
7. "From your own experience of your current degree, which of the following resources do you think would provide added value to your self-directed learning of anatomy?"	(A) Self-directed learning with Sectra (B) Self-directed learning with 3D printed organs (C) Self-directed learning with an online interactive digital embryology resource	1 = strongly disagree 7 = strongly agree
8. From your own experience of your current degree, which of the following reasons make gross anatomy challenging to understand?	(A) Volume of content to learn (B) Teaching contact time (C) Lack of appropriate and effective resources (D) Anatomical terminology (E) 3D spatial relationships of anatomical structures (F) Interpretation of 3D anatomical features in 2D cross-sectional images	1 = strongly disagree 7 = strongly agree

9. From your own experience of your current degree, the development of which of the following skills do you think would enhance your learning of gross anatomy?	(A) Spatial ability (B) Visual observation of anatomical features (C) Haptic observation (touch) (D) Knowledge retention (memory) (F) Making connections in your understanding of different anatomical structures	1 = strongly disagree 7 = strongly agree

Table 5.4: Items of the challenging topics questionnaire in the form of seven-point Likert-type scales.
Some of the questionnaire items were published in the following study (Ben Awadh et al., 2022).

5.5.5 Free-text questionnaire items

Free-text items were designed to investigate students' perceptions of the challenging topics and self-directed learning resources and to gather more information from the students that might not be covered in the Likert-type items. The free-text questions were designed based on the results of the pilot study and on previous work (Backhouse et al., 2017; Keenan et al., 2018). Free-text items in the challenging topic questionnaire included:

- *Please describe any other challenging areas, topics or concepts you have encountered in your learning of gross anatomy that have not been mentioned above.*
- *Please describe any additional taught or self-directed resources that you feel would enhance your anatomy learning further to the resources you currently use.*
- *From your own experience of your current degree, please describe any challenging areas, topics or concepts you have encountered when attempting to interpret anatomical features in cross-sectional clinical images*.

5.5.6 Statistical analysis and semi-quantitative thematic content analysis

To choose the appropriate statistical tests, normality tests were first performed to check the type of data (**Figure 5.2**). The Likert-type data obtained from the questionnaires were classified as non-parametric data after running the Shapiro-Wilk Test and the Kolmogorov-Smirnoff Test, two commonly used statistical tests of normality (Yazici and Yolacan, 2007;

Razali and Wah, 2011; Das and Imon, 2016). To identify the statistical significance between more than three questionnaire items, the Friedman test and pairwise comparison were performed. The Friedman test is a non-parametric test equivalent to the repeated ANOVA measures used for parametric data (Sheldon et al., 1996; Ennos and Johnson, 2012). For comparing two questionnaire items, the non-parametric test that is equivalent to the paired t-test is the Wilcoxon signed-rank test (Harris and Hardin, 2013). The normality tests, Friedman test, and Wilcoxon signed-rank test were all performed using SPSS version 27.0 (SPSS, Chicago, IL, USA).

In addition, a semi-quantitative thematic content analysis was conducted and performed to analyse the free-text questionnaire questions and to check for coherence with the post-positivist theoretical stance of this study. The first step in the semi-quantitative thematic content analysis was a blind double-coding approach of the free-text question data independently performed and reviewed by Dr Iain Keenan (supervisor) and Abdullah ben Awadh (PhD candidate) to explore broader themes and to ensure coherence of the themes that arose from the student responses. Themes arising from the analysis were then combined and the final themes were approved by both reviewers. The next step involved counting the frequency of themes arising from the free-text items, then providing an overview and objective analysis of the content (Franzosi, 2008; Vaismoradi et al., 2013). Finally, the percentage of participating students who gave a response under each theme was calculated (Webb and Choi, 2014; Backhouse et al., 2017).

5.5.7 Focus groups in the first sample

A semi-structured focus group design was used to allow the participants to raise issues that had not been prompted by the moderator. All second-year medical students and the second-year accelerated MBBS students were invited to participate by live announcement at the end of the anatomy lectures. The main aim of the focus groups was to gather more information and perceptions from the students about challenging anatomy topics and how anatomy education can be improved. A group of three second-year accelerated MBBS students at Newcastle University in the academic year 2017/2018 (2AMBBS-17/18) and one second-year MBBS student at Newcastle University in the academic year 2017/2018 (2MBBS-17/18) (**Table 5.3**) were recruited. The focus group discussion was conducted in a prebooked classroom to avoid interruption and to allow the participants to feel relaxed to talk relatively freely. The participants needed to feel relaxed and not pressured by factors that would impede the flow of the conversation or cause them to hesitate to express their opinions (Creswell, 2007). Audio digital recording was applied to accurately record the focus group conversation and to allow the moderator to maintain the flow of the discussion. Notes were also taken by the moderator for use in thematic analysis. The focus group discussion was 35 minutes in length and all four students were given an equal opportunity to provide their insights about the topics and questions. The interview started with an opening question which was followed by several questions (introductory, transition, key, and an ending questions). The focus group questions are presented in **Table 5.5**. The recorded focus group conversation was then transcribed. A double-coded thematic analysis (Smith et al., 2017) was conducted by Dr Iain Keenan (supervisor) and Abdullah ben Awadh (PhD candidate) using NVivo version 12 Pro (QRS International Pty Ltd., Melbourne, VIC, Australia), a qualitative data analysis software.

Description	Focus Group Questions
Opening Questions	1- Is anatomy an important component of your current degree and why?
	2- Compared to other basic sciences, is gross anatomy a challenging component of your current degree?
Introductory Question	3- Do you think that there are challenging topics in gross anatomy and why?
Transition Question	4- From your experience, which of the following topics do you think is the most challenging and why? (Gross Anatomy, Clinical Imaging, Embryology, Histology, Microanatomy)
Key Questions	5- Which anatomical region do you find the most challenging and why?
	6- Can anyone tell me the visceral organ for which it is most challenging to understand structures and functions?
	7- Are there difficulties in interpretation and understanding the anatomical features in cross sectional images?
	8- From your experience, do you think 3DP, SECTRA and Digital Embryology Resources will help you with self-directed learning of anatomy?
	9- Do you think that the development of some skills can enhance your learning of anatomy? If yes, what are these skills?
Ending Question	10- Is there any more information you would like to add that hasn't been discussed?

Table 5.5: Focus group questions.
The questions that were posed to the participating students in the focus group.

5.5.8 Qualitative thematic analysis

The data, including the transcript of the focus group conversation, were prepared before the data were analysed. The transformation of the recorded focus group conversation into a full transcript was an important analysis step as it allowed the researcher to become familiar with what had been discussed in the focus group. The thematic analysis in this research followed the six-step framework of Braun and Clarke (Braun and Clarke, 2006) as discussed earlier in this chapter (**Section 5.3.9**). The transcript was read by the researcher many times to gain familiarity with the materials and to focus and highlight the important points. NVivo version 12 Pro (QRS International Pty Ltd., Melbourne, VIC, Australia) was used to help organise the extracted codes. Data analysis started with the generation of initial codes to identify important features of the data that referred to meaningful points describing a phenomenon (Boyatzis, 1998; Braun and Clarke, 2006). Moreover, codes represent detailed information that leads to broader areas or topics, known as themes. The theme-generation phase is the process of refocusing the analysis at a broader level to include all the extracted codes under one theme. To avoid bias, a double-coded thematic analysis was conducted by Dr Iain Keenan (supervisor) and Abdullah ben Awadh (PhD candidate). The final report obtained from the thematic analysis of the focus group data is presented in the results chapter (**Section 6.1.8**).

5.6 Phase II Methods: Practical Multimodal 3D Anatomy Learning

5.6.1 Study design

A pilot study was performed to help plan the full study design, and only the Sectra was used. Only 5 SSC students participated in the pilot study, and they used the Sectra and 2D images. There was a pre-test before the polit activity and post-test at the end to compare the student performance, and a Likert-type questionnaire was provided to the students to gather their insights. The results of the pilot study are shown in **Section 6.2.6** of the results chapter.

The second phase of the project involved the implementation of a multimodal learning activity involving the Sectra VT and 3DP models, embedded within practical anatomy sessions. This activity was intended to enhance the learning and experience of novice students when attempting to reconcile an understanding of 3D and cross-sectional anatomy during the process of clinical-image interpretation. The impact on learner performance of having used this combination of Sectra and 3DP models was compared to learner performance following the use of 2D static cross-sectional images as the control. This comparison was made using experimental pre-post testing. The control activity was designed to recreate a clinical image learning activity that was previously delivered at MSNU prior to the availability of Sectra and 3DP technology. Experimental testing, questionnaires, and focus groups were the three data-gathering methods. An MR test (MRT) (**Section 5.3.3**) was administered to investigate any potential relationship between learning performance and spatial ability. The full study design is explained in **Figure 5.7** and **Figure 5.9**. The learning activities for both intervention and control learning activities were designed as small group activities to conform to the social constructivism theory (**Section 2.1**). In addition, the intervention learning activity was introduced in practical sessions in which each step of the KELC involved an activity in the practical session (**Section 2.2**). The learning activities for the intervention were in case 1 and the learning activities for the control were in case 2 (**Figure 5.3**).

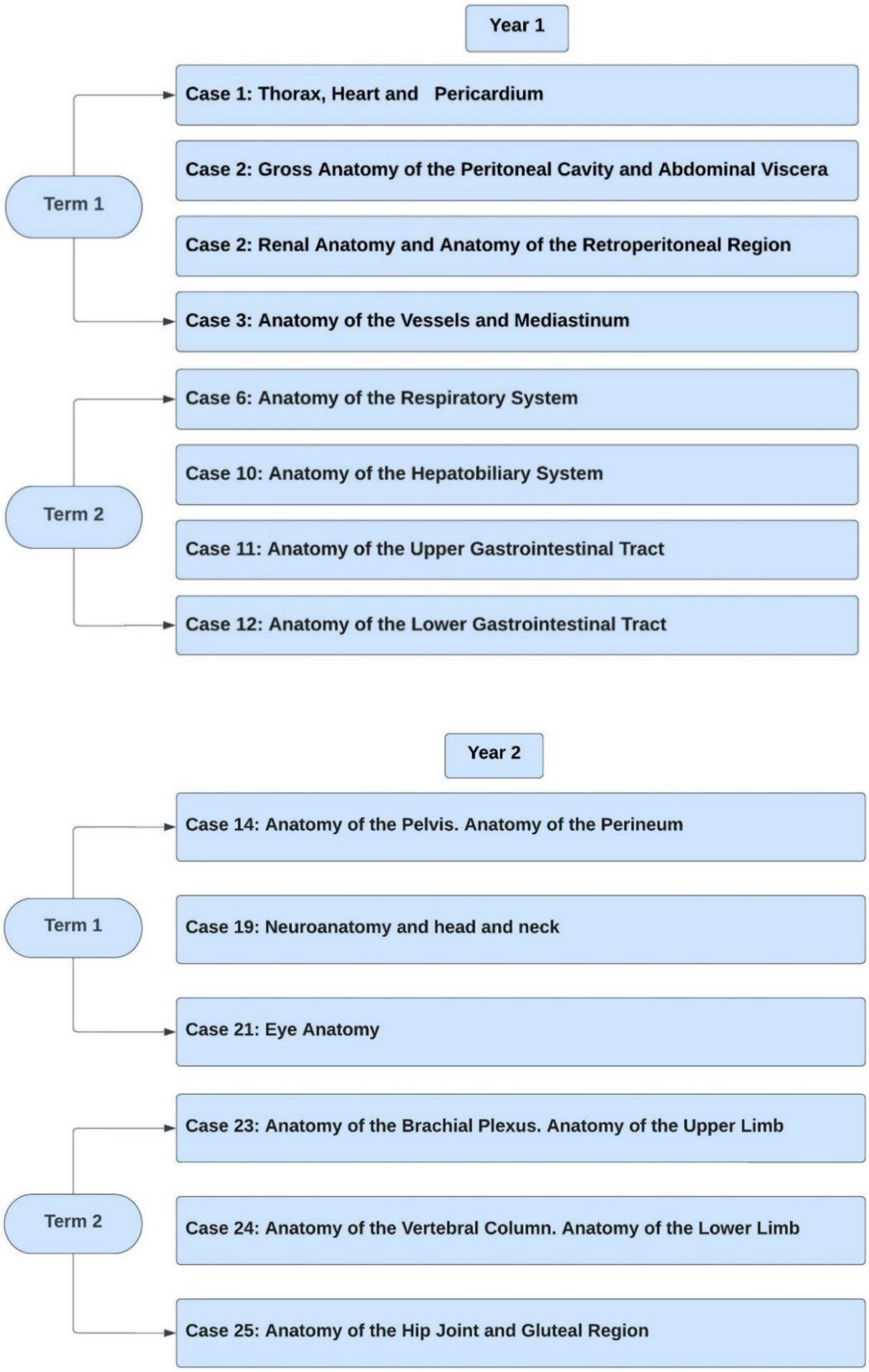


Figure 5.3: Timeline for the anatomy cases for year 1 and year 2 medical students (2018/2019).

5.6.2 Development of a multimodal clinical image interpretation activity (intervention).

A novel practical learning activity intended to support novice learner interpretation of transverse CT images was developed. A multimodal approach, combining the use of the Sectra VT to display CT images and 3D renderings of anatomical features and bespoke 3DP models was constructed from real patient data. The Sectra Terminal VT model F18 (**Figure 5.4**) (Sectra AB, Linköping, Sweden)(Keenan and ben Awadh, 2019a) was used to show and display transverse cross-sectional CT stacks, which can be digitally rendered in real-time within the Sectra picture archiving and communication system (PACS) software into interactive 3D digital models of the thorax.

PACS provides the user with access to all the tools required to review studies and to document reports that include 3D rendering clinical applications, such as Secta vessel analysis and Sectra anatomy linking, and display radiology protocols and scans, such MRI and CT scans (Sectra, 2021c). Moreover, a collection of identical 3DP models (**Figure 5.5**) printed in-house were used to provide a physical representation of the location, size, and shape of the heart and to support understanding of the Sectra visual display of the heart.

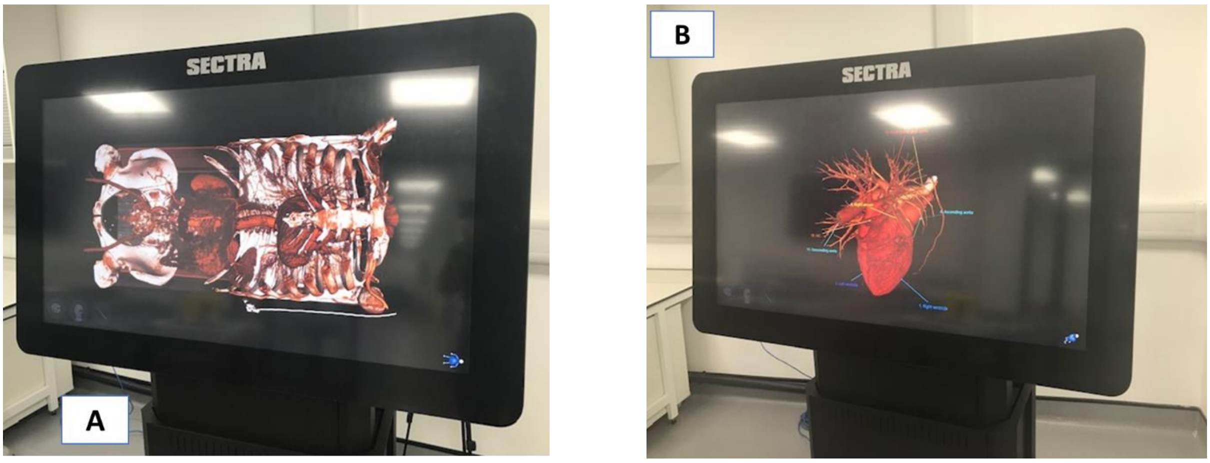


Figure 5.4: The Sectra Terminal VT (Sectra).
Figures A and B show a 3D digital model rendered from a CT scan used for the Sectra and 3DP model learning activities.

The 3DP heart models were deliberately designed to be simple models that provide accurate anatomical size, shape, and position of a human heart, but without the extraneous detail of a complex commercial model or the realism and tactile sensation of a cadaveric heart. Moreover, 3DP heart models could be handled without gloves, are less susceptible to damage, and remained in a solid shape to support orientation and identification of equivalent vertebral levels. Comparing complex 3D printed models and commercial models (Sweller, 1988; Van Merriënboer and Sweller, 2010; Dror, 2011), the simplified appearance of the accurate 3DP model reduces cognitive load on the novice student during first exposure to anatomy in the practical sessions (Khalil et al., 2005a; Dror, 2011; Van Nuland et al., 2015; Küçük et al., 2016). 3DP models are inexpensive to produce and print compared with commercial anatomical models (Li K, 2017; Smith et al., 2017; Keenan and ben Awadh, 2019a). High-quality anatomy models are very expensive. For example, a thorax model containing the lungs and heart can cost £738.00 (Adam, Rouilly Company), and such models cannot be removed from the DR for self-directed study.

Open access software that is freely available was used to produce and to create refined stereolithography (.STL) files from DICOM-formatted images (Keenan and ben Awadh, 2019a) while committing to regulations and guidelines for appropriate use of anonymised patient data from the UK Royal College of Radiologists (RCR, 2020a).

The steps for printing a 3DP model start with the utilization of 3D slicer software version 4.8 (Harvard Medical School, Boston, MA) (Fedorov et al., 2012) to isolate the heart from cross-sectional CT images for segmentation, isolation, and thresholding in DICOM format. Next, Blender version 2.8 (Stichting Blender Foundation, Amsterdam, The Netherlands) and Meshmixer version 3.5 (Autodesk Inc., San Rafael, CA), were used for cleansing, smoothing, and refining the 3D digital model of the heart and to export the final model as an .STL file. Finally, the .STL files were imported to ideaMaker version 3.1 (Raise 3D Technologies, Inc., Irvine, CA), a 3DP slicing software, for the final step of editing and adding support structures (**Figure 5.5**) to guarantee model strength and stability during printing. The printing stage starts by transferring the final edited .STL file to the 3DP printer (Pro2 3D printer, Raise 3D Technologies, Inc., Irvine, CA) (**Figure 5.5**) via a flash memory drive to print the final physical model. Printing times vary depending on the size of the 3DP model and the amount of detail.

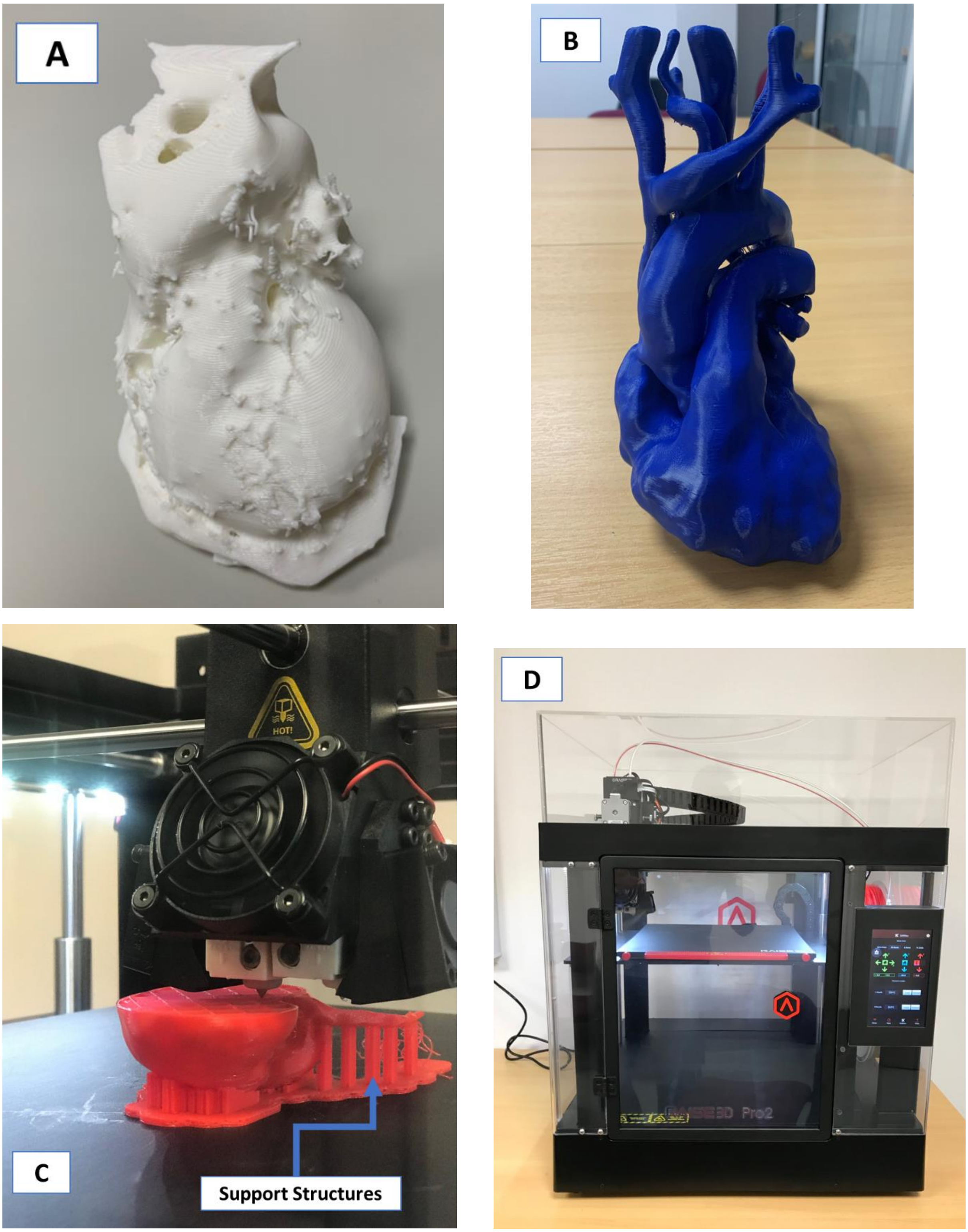


Figure 5.5: 3D printers and examples of 3DP models
Figures **A** and **B** show examples of 3DP models used in the Sectra + 3DP model learning activity to show and demonstrate the shape, position, and size of the heart in 3D. **C** shows the printing process of a 3DP model where the support structures that hold the model are shown; **D** is the Pro2 3D printer (Raise 3D Technologies, Inc., Irvine, CA) used in this project.

After designing the learning activity for the Sectra and 3DP models, a **pilot study** was conducted with the PA students (PAs-18/19). The aim of the pilot study was to refine the learning activity, ensure the quality of the 3DP models, and evaluate the clarity of the learning activity steps and materials. At the end of the pilot study, the PA students (**PAs-18/19**) were asked to complete a questionnaire about Sectra and 3DP model use (**Section 6.2.1, 6.2.2**).

Based on the findings of the pilot study, the Sectra and 3DP model learning activities were implemented into Case 1 "Thorax, Heart, and Pericardium" of the first-year medical programme early in October 2018 as part of the cardiovascular anatomy practical session (**Figure 5.3**). The Sectra was used to display images from Sectra PACS software (Sectra, 2021c), version 20.2 (Sectra AB, Linköping, Sweden) and the SEP (Sectra AB, Linköping, Sweden). The CT stack under the case number "Case S113 Thorax F" (**Figure 5.6**) was used for the Sectra visualisation table and 3DP model intervention activity.

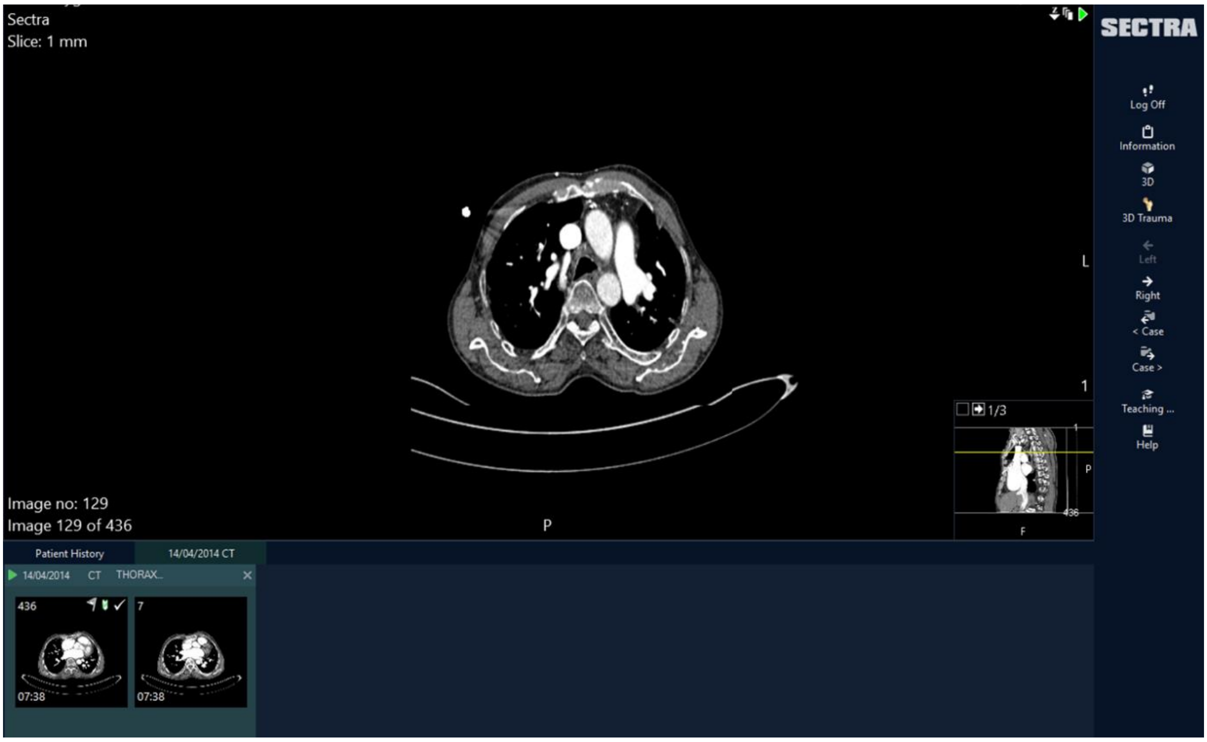


Figure 5.6: Sectra VT screenshot
The figure shows an example of an individual axial computed tomography scan used in the intervention learning activity (Sectra and 3DP models)

During the intervention activity, one sub-group (n ≈ 8–9) of learners was offered four identical 3DP models of the heart to interact with by holding, rotating, sharing, observing, and palpating. The group demonstrator began the learning activity by handing out a task sheet (**Appendix**) and explaining the simple basis for interpreting the CT scan, as this was the students' first experience of imaging interpretation in the practical session for the academic year 2018/2019 (**Table 5.3, Figure 5.3**). The demonstrator explained the patient position in the CT scan, i.e., that the patient's left side is the viewer's right side when looking at the screen and that the patient is laying face up (supine position). A task sheet was used to provide consistency across all sessions. The students were asked to distinguish and identify the anterior/posterior and left/right orientation of the scan and to explain the black areas on the scan (air). In addition, the students were asked to distinguish and identify some of the anatomical structures that contained air, such as the trachea and the lungs (Ben Awadh et al., 2022). The demonstrator then scrolled through an axial CT scan from superior to inferior beginning at the 7th cervical vertebra (C7) to the inferior level of the xiphoid process corresponding to the 10th thoracic vertebra (T10). The demonstrator then scrolled down to the level of the aortic arch and asked students to distinguish and identify the anatomical structures that appeared in white on the CT scan (blood vessels and bone) (Ben Awadh et al., 2022). Students then were asked to identify the three circular structures projecting from the superior side of the aortic arch (brachiocephalic trunk, left common carotid artery, and left subclavian artery).

It is important to note that some of the structures that appeared in the CT scan were not visible on the 3DP model because the 3DP model was mainly used to present the shape, position, and size of the heart itself. The intervention learning activity continued by scrolling down through the heart at the level of the axil cross-section to identify the pulmonary trunk (large vessel) and the heart chamber (right ventricle) from which it branched and to analyse and relate the location and appearance of these anatomical features and structures on the 3DP models that the students held during the session. Some of the discussed structures were labelled on the CT stack. All students in the session were then asked to identify the position of the heart chambers by holding the 3DP models of the heart in the correct anatomical position. The demonstrator scrolled down on the axial cross-sectional scans to the level at which all the heart chambers could be seen at the T8 vertebral level and the students were asked to name and distinguish the four chambers of the heart on the screen and explain how these related to the chamber positions on the 3DP models (Ben Awadh et al., 2022). The demonstrator emphasized that all four chambers of the heart could be viewed in a cross-section at the T8 level due to correct anatomical positioning. The '3D render' option in the Sectra VT was selected by the demonstrator to create a 3D digital image and models of the thorax in real-time from the same CT stack being viewed and observed in the practical session (Ben Awadh et al., 2022). The demonstrator then interacted with the digital image and rotated it in many directions to provide different 3D views of the heart. The 'virtual knife' in the software was used to remove the sternum to view the anterior side of the heart. The demonstrator then dissected an axial plan through the heart to reveal the four chambers in cross-section, emphasise the 3D structures of the heart, and view the axial plane, while the participating students referred to the physical 3DP models (Ben Awadh et al., 2022).

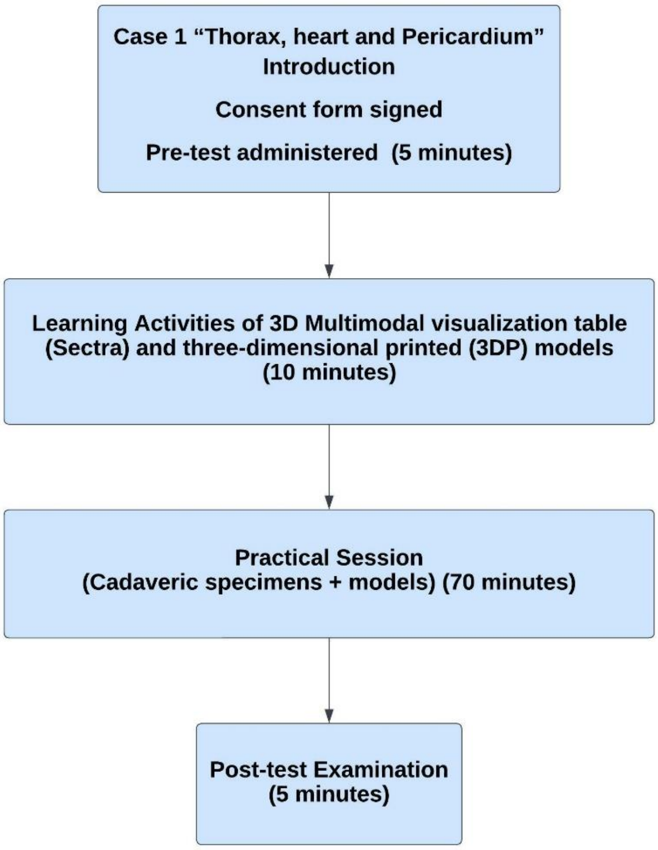


Figure 5.7: Flowchart of the learning activities using the 3D multimodal VT (Sectra) and 3DP models (intervention).

5.6.3 Development of a 2D cross-sectional clinical image interpretation learning activity (control).

The aim of the control learning activity for 2D clinical image interpretation was to replicate the standard delivery of cross-sectional clinical imaging teaching within the medical curriculum at Newcastle University prior to digital multimodal visualisation technologies and 3DP model resources becoming available for cross-sectional anatomy learning (Ben Awadh et al., 2022). The control learning activity (2DX) was implemented during Case 2 of the medical programme in the practical session of “Gross Anatomy of the Peritoneal Cavity and Abdominal Viscera” during late October and early November 2018 (**Figure 5.3**) (Ben Awadh et al., 2022). During the control learning activity, the Sectra VT was not used in the practical session.

A PowerPoint presentation of axial cross-sectional images through the abdomen was created using screenshots of images taken from the VHD Pro software, version 5.2.62 (Touch of Life Technologies, Aurora, CO) (**Figure 5.8**). The study was designed to generate a clinical-image interpretation activity using only 2D cross-sectional images (**Figure 5.9**). A slideshow consisting of seven cross-sectional images from the 9th thoracic vertebra (T9) to the 3rd lumbar vertebra (L3) was presented to the students during the practical session. The design of the control learning activity was similar to that of the intervention with regard to the size of the sub-group (n ≈ 8–9 students) and the volume of content. The important anatomical structures and features were labelled in each slide to provide more information, and the size of the structures to be identified were similar to those in the intervention learning activity. The slideshow was presented on a large screen in the DR and the demonstrator explained the major and important anatomical features to a sub-group of approximately eight students. It is important to note that only fixed images were used during the control learning activity, and the interactive functions of the VHD software, including dynamic 3D and cross-sectional features (Fogg, 2007) were not used, so that a comparison of the effect of static 2D images resources and the 3D resources used in the intervention activity could be made.

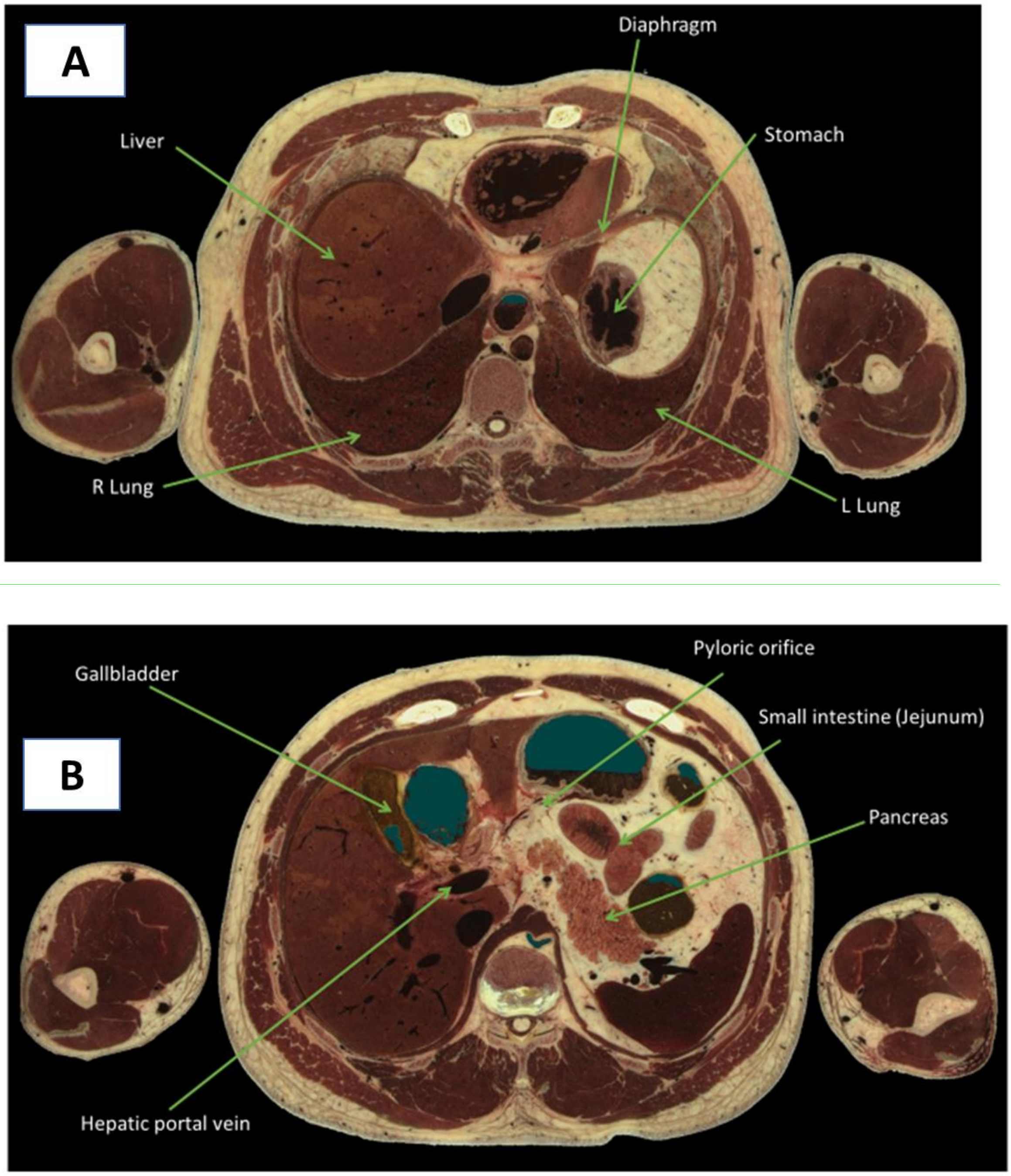


Figure 5.8: Example of modified static images from VHD Pro.
A and B show examples of labelled images added by the researcher and used in the control two-dimensional cross-section (2DX) learning activity.

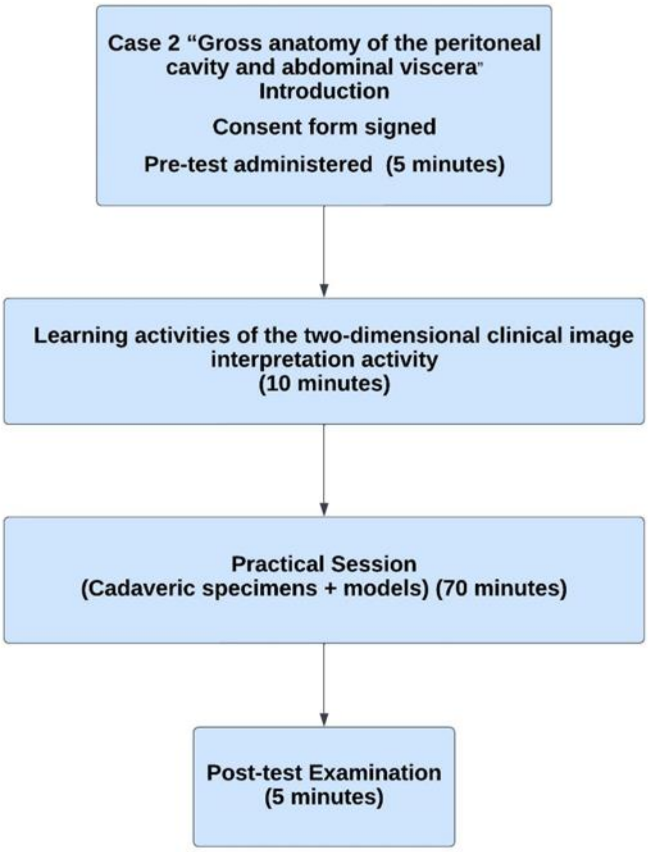


Figure 5.9: Flowchart of the learning activities of the 2D cross-sectional clinical-image-interpretation activity (control).
The learning activity involved one station during the practical session.

5.6.4 Recruitment and sampling

For the post-2017 first year medical curriculum (2018/2019), a census sampling approach (Suresh et al., 2011) was implemented to sample the total student cohort (n = 335, median age 18 years at commencement of studies). The census sampling approach was chosen to ensure that the questionnaire and the experimental tests were given to all the participating students in the study in order to gain an unbiased view of the results (Suresh et al., 2011). In addition, the project employed a simple random sample in which all students had an equal chance of participating in the study (Singh, 2003; Cohen et al., 2018e). This part of the study included 319 student participants, and those who responded gave their consent to participate. The response rate was 95% and we needed at least 178 students to reach a 95% CL. The responding cohort consisted of 140 (44%) male and 179 (56%) female students. The experimental testing part of the study involved 229 first-year medical students (2018/2018) with a response rate of 68%, and 313–318 students responded to Likert-type questionnaire items. Considerable participant attrition occurred with respect to free-text items. Students responded to free-text items regarding Sectra (n = 118), 3DP models (n = 86), and future recommendations (n = 121).

5.6.5 MR test

The designed MR test (MRT) was administered with complete instructions to first-year medical students (**Table 5.3**) early in October in the academic year 2018/2019 prior to any anatomy teaching. The MRT contained 10 problem sets of geometric shapes (**Figure 5.1**). Each set contained one model and four alternative options. Students were required to choose the two correct images from the four options that represented correct rotations of the original shape. Participants were allowed exactly five minutes to answer the 10 problems and submit the test. One point was allocated for each correct response, resulting in a maximum possible score of 20/20. To examine any relationship between individual MRT test scores and student performance in the intervention activity (Sectra + 3DP models) and in the control active (2DX), a regression analysis was performed. Correlation thresholds were defined in advance, where R^2 = 0.8−1 indicates a very strong correlation; R^2 = 0.6−0.79 indicates a strong correlation; R^2 = 0.4−0.59 indicates a moderate correlation; R^2 = 0.2−0.39 indicates a weak correlation; and R^2 = 0−0.19 indicates a very weak correlation (Campbell, 2021b).

5.6.6 Experimental testing and statistical analysis

During October and November 2018 in the first term of the academic year 2018/2019, pre- and post-tests of cross-sectional clinical-image interpretation were administered before and after the first-year anatomy practical sessions in Case 1 and Case 2 (**Figure 5.3**).

The pre-test was a closed-book test performed to identify baseline knowledge prior to the learning activities involving the Sectra and 3DP models (intervention) and the 2D learning activities (control). A closed-book post-test was performed to measure improvements and knowledge gained following participation in the intervention and control learning activities. Each test consisted of 12 questions that required the students to identify labelled structures in sagittal and axial cross-sectional images in the format of CT scans and plain radiographs taken from Sectra PACS software, version 20.2 (Sectra AB, Linköping, Sweden) and from the VHD Pro software, version 5.2.62 (Touch of Life Technologies, Aurora, CO) of the related region (Ben Awadh et al., 2022).

Cross-sectional clinical images of the thorax were used for the intervention activity. The five-minute pre-test was administered to students at the beginning of the practical session (**Figure 5.7**). The students then engaged in a 10-minute learning activity with the use of the Sectra and 3DP models as part of a wider practical session on the anatomy of the thoracic and cardiovascular tissues. At the end of the practical session, a five-minute post-test was administered to the students. Cross-sectional images of the abdomen were used in the testing of the 2D clinical images interpretation activities (control). Similar to the intervention learning activities, students took the pre-test at the start of the practical session and the post-test at the end of the session, and they were given five minutes to complete each test.

It is important to note that the pre- and post-tests for the control and the intervention activities were very similar to each other in terms of labelling structures and the type of images used. The tests were designed specifically to test understanding and knowledge gained from the Sectra and 3DP learning activity and from 2DX cross-sectional learning activities rather than knowledge that could have been gained elsewhere in the session.

The students participated in a 10-minute 2D clinical-image interpretation activity as part of the abdomen practical session that was scheduled 2–3 weeks after the thoracic practical session. Student performances for the Sectra and 3DP activity and the 2DX activity were calculated by detecting changes in pre-post test scores.

Applying two common statistical tests of normality, the Shapiro-Wilk test and the Kolmogorov-Smirnoff test, we found that pre-test and post-test data were parametric. To identify statistical significance between parametric pre-test and post-test data, a paired t-test analysis was performed. Box plot analysis is a statistical test used to visually identify patterns that could otherwise be hidden (Williamson et al., 1989). Box plots are becoming a commonly used tool in investigative data analysis as they introduce visual summaries of data that are alternatives to tables when comparing variables and distinguishing patterns (McGill et al., 1978; Williamson et al., 1989). In this project, a box plot analysis was performed to provide a visual comparison between mean performance data for the intervention learning activity (Sectra and 3DP models) and the control activity (2DX). The thresholds were defined as statistically highly significant if $P < 0.001$ and statistically significant if $P < 0.05$ (McCrum-Gardner, 2008; Andrade, 2019). The test score percentage and performance were calculated from participant mean data.

5.6.7 Questionnaires and statistical analysis of the data

Physical paper questionnaires were administered to first year medical students during the practical session of Case 2 “Anatomy of the Kidney”, which was delivered during the week following the control learning activity for the 2D clinical-image interpretation (**Figure 5.3**) (Ben Awadh et al., 2022). A seven-point Likert-type questionnaire (Leung, 2011) was designed based on previous research (Backhouse et al., 2017; Keenan et al., 2018) and was modified based on the results of a pilot questionnaire. In the study, the internal consistency of the questionnaire items was determined using Cronbach’s alpha test, which was calculated post hoc to ensure reliability and internal consistency of the questionnaire items. A value of 0.82 was determined, where a value of 0.7–0.9 is considered to be acceptable (Tavakol and Dennick, 2011). The first-year medical students who completed the questionnaire undertook the anatomy topics presented in **Table 5.6** within the post-2017 medical programme curriculum.

Topic	**Teaching Method**
“Introduction to anatomical terms”	Lectures
“Structure of the heart”	Lectures
“Internal anatomy of the heart”	Lectures
“Anatomy of the peritoneal cavity”	Lectures
“Thorax, heart and pericardium”	Practical sessions
“Gross anatomy of the peritoneal cavity and abdominal viscera”	Practical sessions
“Renal anatomy and anatomy of the retroperitoneal region”	Practical sessions
“Introduction to clinical imaging”	Self-directed learning
“Clinically relevant anatomy of the peritoneal folds”	Self-directed learning
“Clinically relevant anatomy for bladder catheterization”	Self-directed learning

Table 5.6: Anatomical topics undertaken by first-year medical student.
The first-year medical students in the 2018/2019 medical programme curriculum undertook the anatomical topics included in the table with different teaching methods (Ben Awadh et al., 2022).

The questionnaire was divided to three sections. The first section covered challenging anatomical topics, the second section covered use of the Sectra, and the third section covered use of 3DP models. The questionnaire items for all sections are shown in **Table 5.7**, **Table 5.8**, and **Table 5.9**. Normality tests were performed on the Likert-type data to choose the most appropriate statistical tests.

The data obtained from the questionnaire were identified as non-parametric, so Friedman testing and pairwise comparison were performed to identify statistical significance when comparing more than three questionnaire items. A Wilcoxon signed-ranks test analysis was performed on the non-parametric data obtained from the questionnaire when comparing two questionnaire items.

In this project, the thresholds were defined as being highly statistically significant if $P < 0.001$ and statistically significant if $P < 0.05$. The mean and standard deviations obtained from each item of each questionnaire statement were used in the statistical analysis of the data.

Questionnaire item	**Sub-item**	**Seven-point Likert-type scale range**
1- "From your own experience of your current degree, how challenging has it been to learn the following anatomical topics?"	(A) Gross Anatomy (B) Surface Anatomy (C) Clinical Imaging	1 = not at all challenging 7 = extremely challenging
2- "From your own experience of your current degree, how challenging has it been to learn the following anatomical regions?"	(A) Abdomen (B) Thorax	1 = not at all challenging 7 = extremely challenging
3- "From your own experience of your current degree, how challenging has it been to understand the gross anatomical size, shape, position, and structure of the following anatomical features?"	(A) Heart (B) Kidney (C) Peritoneum	1 = not at all challenging 7 = extremely challenging
3- "From your own experience of your current degree, which of the following make learning gross anatomy challenging?"	(A) Volume of content to learn (B) Teaching contact time (C) Lack of appropriate and effective resources (D) Anatomical terminology	1 = strongly disagree 7 = strongly agree

	(E) 3D Spatial relationships of anatomical structures (F) Interpretation of 3D anatomical features in 2D cross-sectional images	
4- From your own experience of your current degree, development of which of the following skills do you think would enhance your learning of gross anatomy?	(A) Spatial ability (B) Visual observation of anatomical features (C) Haptic observation (touch) (D) Knowledge retention (memory) (F) Making connections in your understanding of different anatomical structures	1 = strongly disagree 7 = strongly agree
5- "From your own experience of your current degree, how challenging has it been to identify the anatomy of the following anatomical features in **<u>cross-sectional images?"</u>**	(A) Abdomen (B) Thorax	1 = not at all challenging 7 = extremely challenging

Table 5.7: Questionnaire items on the challenging topics for Phase II of the study.
The questionnaire was designed in the form of a seven-point Likert-type scale.
Some of the questionnaire items were published in a following study (Ben Awadh et al., 2022).

Questionnaire item	Seven-point Likert-type scale range
1- Sectra improved my understanding of the three-dimensional gross anatomy of the thorax.	1 = strongly disagree 7 = strongly agree
2- Sectra improved my understanding of the gross anatomy of the thorax in cross-sectional images.	1 = strongly disagree 7 = strongly agree
3- “Physically interacting with the Sectra screen was important in improving my understanding of anatomy and cross-sectional images” (please leave blank if you did not interact with the screen).	1 = strongly disagree 7 = strongly agree
4- “Sectra was more valuable for my learning of gross anatomy and clinical image interpretation than using static 2D cross-sectional images.”	1 = strongly disagree 7 = strongly agree
5- I found the 3D rendered images on Sectra valuable for my learning.	1 = strongly disagree 7 = strongly agree
6- “Sectra would be a useful self-directed learning resource for studying three-dimensional and cross-sectional gross anatomy.”	1 = strongly disagree 7 = strongly agree

Table 5.8: Questionnaire items on Sectra use in Phase II of the study.
The questionnaire was designed in the form of a seven-point Likert-type scale. Some of the questionnaire items were published in a following study (Ben Awadh et al., 2022).

Questionnaire item	Seven-point Likert-type scale range
1- "Using 3DP models during the practical session was valuable for my learning."	1 = strongly disagree 7 = strongly agree
2- The use of 3DP models improved my 3D understanding of the heart.	1 = strongly disagree 7 = strongly agree
3- "Using 3DP models outside of the DR would be a valuable self-directed learning resource for studying anatomy."	1 = strongly disagree 7 = strongly agree

Table 5.9: Questionnaire items on 3DP model use in Phase II of the study.
The questionnaire was designed in the form of a seven-point Likert-type scale. Some of the questionnaire items were published in a following study (Ben Awadh et al., 2022).

5.6.8 Free-text questionnaires and semi-quantitative content analysis

The free-text items were part of the Likert-type questionnaire administered to first-year medical students during the practical session of Case 2 *'Anatomy of the Kidney'* (**Appendix**). The free-text items were designed based on previous work (Backhouse et al., 2017; Keenan et al., 2018) and by the steps discussed in **Section 5.3.4**. After generating the free-text items, pilot testing and collaboration were performed by Dr Iain Keenan (supervisor) and Abdullah ben Awadh (PhD candidate) to validate and refine the items. The free-text items included below and some of the free-text questionnaire items were published in a following study (Ben Awadh et al., 2022):

- *Please describe any other challenging areas, topics or concepts you have encountered in your learning of **gross anatomy** that were not mentioned above.*
- *Please describe any additional taught or self-directed resources that you feel would enhance your **gross anatomy** learning further to the resources you currently use.*
- *"If you physically interacted with the Sectra screen, please briefly describe why this interaction was/was not important in improving your understanding of anatomy and cross-sectional images."*
- *"Do you have any suggestions on how we can improve the use of Sectra?"*
- *"Do you have any suggestions on how we can improve the use of 3DP models?"*

To interpret the qualitative free-text data, a semi-quantitative thematic content analysis was conducted to be coherent with the post-positivist theoretical stance of the study. The semi-quantitative thematic content analysis was performed based on previous studies (Franzosi, 2008; Vaismoradi et al., 2013; Backhouse et al., 2017; Keenan et al., 2018) and on the steps described previously in **Section 5.3.8.**

5.6.9 Focus group and qualitative thematic analysis

At the end of the first term of the academic year 2018/2019, the first-year medical students (1MBBS-18/19) were asked to participate in a focus group. This was publicised via in-person announcements by the researcher after the anatomy lectures and by emailing only the students who agreed to participate by providing their email when they completed the questionnaire. Only three students out of the total cohort (n = 335) were interested in joining the focus group. To avoid interruption and distraction, the focus group was scheduled to take place in a prebooked classroom. The steps to perform the focus group were described earlier in this chapter (**Sections 5.3.5, 5.5.7**). The focus group discussion took 37 minutes, and the discussion was audio digitally recorded. The recorded discussion was then transcribed verbatim. The collected data from the transcript were analysed using qualitative thematic analysis as described earlier in this chapter (**Section 5.3.9, 5.5.8**) and by using NVivo version 12 Pro (QRS International Pty Ltd., Melbourne, VIC, Australia) which is a qualitative data analysis software package.

5.7 Phase III Methods: Remote Multimodal 3D Anatomy Learning

5.7.1 Study design

The third phase of the project involved the implementation of the SEP as a self-directed learning resource. In this section, the benefits of implementation the SEP in the medical curriculum are investigated using experimental testing, a questionnaire, and a focus group. The study was performed in two parts; part 1 took place prior to the COVID-19 pandemic and part 2 took place after the COVID-19 pandemic. The full study design for part 1 and part 2 is explained in **Figure 5.10** and **Figure 5.11**.

5.7.2 Developing **SEP learning activities prior to the COVID-19 pandemic (Part 1)*.***

The control learning activity was implemented early in October of the academic year 2019/2020 for first year medical students (Group 1) (**Table 5.3, Figure 5.3**). The design of the control learning activity was a replica of the Sectra and the 3DP model learning activity

(**Section 5.6.2**). The learning activity of the Sectra and the 3DP models was implemented into Case 1 *'Thorax, Heart and Pericardium'*. The practical thorax session started with a brief explanation about the session. All the information about the session was introduced to all participants on the same day to avoid foreknowledge or crosstalk bias (Edlund et al., 2009). The participants then completed a five-minute pre-test to determine their baseline knowledge about the thorax. After the pre-test, the students were divided to subgroups of 8–10 students and the practical session continued. During the session, each subgroup used the Sectra and 3DP models for 10 minutes. The demonstrators were given a task sheet (**Appendix**) to access the Sectra case and to address the case objectives. After two weeks, the same first-year medical students completed a delayed post-test.

The design of the intervention learning activity involved the implementation of the SEP as a remote multimodal 3D anatomy learning resource (**Figure 5.10**).

The SEP learning activity was implemented after the Case 2 practical session 'Gross Anatomy of the Peritoneal Cavity and Abdominal Viscera' in late October and early November 2019 (Ben Awadh et al., 2022). The SEP (Sectra AB, Linköping, Sweden) is a subscription-based PACS platform that provides anonymous clinical cases (Sectra, 2021b). The SEP is an interactive cloud-based sharing resource providing access to a many diagnostic and clinical images for manipulation, modification, and visualisation, and it allows the user to access, view, interact with, and modify clinical cases and other teaching materials. Access to the SEP is achieved using educator or student login credentials provided via an institutional licence. The SEP can be accessed either via the Sectra Table, or from other any workstation. At the time of the research, the students could therefore access the 'Sectra UniView' via the SEP using their student license on any iOS or Android tablet or smartphone remotely and outside of the classroom in order to view 2D cross-sectional images and 3D image stacks that had been added and or/modified by educators (Sectra, 2021b). The portal consists of real-world clinical images in highest-quality 3D, together with case histories and bookmarks with highlighted structures and annotations. The SEP can be integrated into traditional teaching methods (lectures) or can be used for remote teaching and self-directed learning purposes.

The SEP was used to deliver the same taught content materials that were displayed on the Sectra after practical anatomy sessions. Students completed a pre-test before the Case 2 practical session. After the Case 2 practical session, all of the first-year medical cohort received an email with a username and password to access the SEP on their own devices for the purposes of self-directed study. The students were asked to complete a SEP tutorial guide (**Appendix**) on the MLE.

The SEP tutorial guide provided the students (**Group 1**) with an introductory guide for accessing and using the portal to complete learning activities focusing on identifying prominent structures and features of the abdomen in cross-sectional clinical images and 3D digital images. The SEP learning activity was designed and implemented to deliver the case learning outcomes. A delayed post-test was administered to the students two weeks after the implementation of the SEP tutorial guide on the MLE. Both the pre-test and the delayed post-test were similar to the tests in Phase II. The design and analysis of these experimental tests is discussed in **Sections 5.3.3**, **5.3.6**, and **5.6.6.**

At the end of term, consenting first-year medical students (Group 1) completed a Likert-type questionnaire (**Table 5.10**) with free-text questionnaire items to gather their perceptions of their use of the SEP. The free-text items included below and some items were published in a following study (Ben Awadh et al., 2022):

- *"Please describe why your interactions with the* SEP *were/were not important in improving your understanding of 3D and cross-sectional anatomical features."*
- *"If you used touch screen device(s) with the* SEP*, please describe why this was/was not important in improving your understanding of anatomical features in 3D images and cross-sections."*
- *Please describe any OTHER resources you used with the* SEP *in order to complete any part of the CASE 2* SEP *GUIDE: 'ANATOMY OF THE ABDOMINAL VISCERA'?*
- *Please describe any self-directed anatomy and clinical imaging resources (other than the* SEP*) that you currently/previously used in your own time for study or revision (outside of timetabled teaching). Anatomy resources/ Imaging resources*
- *Please describe any other suggestions you may have for improving how we use the* SEP.

The steps to design and analyse the questionnaire items are discussed earlier in this chapter **(Sections 5.3.4**, **5.3.8**, **5.5.4**, **5.5.5**, and **5.5.6).** In December 2019, four students participated in a focus group to discuss the benefits of using the SEP. The focus group design and the thematic analysis steps are discussed in **Sections 5.3.5**, **5.3.9**, **5.5.7**, and **5.5.8.**

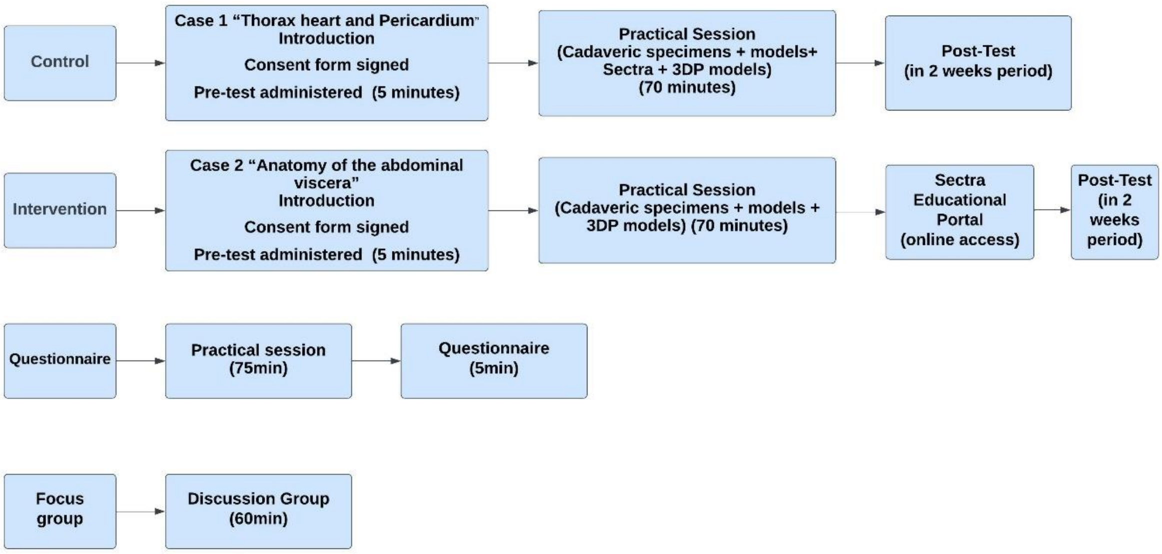


Figure 5.10: Flowchart showing the implementation of SEP learning activities prior to the COVID-19 pandemic (Part 1).

Questionnaire item	Seven-point Likert-type scale range
1- The SEP improved my understanding of 3D gross anatomy of the abdomen	1 = strongly disagree 7 = strongly agree
2- The SEP improved my understanding of the gross anatomy of the abdomen in cross-sectional images.	1 = strongly disagree 7 = strongly agree
3- The ability to actively interact with and manipulate SEP images was important for improving my interpretation of 3D anatomical features in cross-sectional images	1 = strongly disagree 7 = strongly agree
4- Using 3D printed anatomical models with the SEP would further enhance my learning	1 = strongly disagree 7 = strongly agree
5- The SEP is a valuable self-directed learning resource for studying 3D and cross-sectional anatomy and I wish to use the SEP for studying anatomy again in the future.	1 = strongly disagree 7 = strongly agree
6- I would recommend the SEP to other medical students for their anatomy learning	1 = strongly disagree 7 = strongly agree

Table 5.10: Questionnaire items on the SEP usage questionnaire in the form of seven-point Likert-type scales.

5.7.3 Developing SEP learning activities after the COVID-19 pandemic (Part 2).

As described in **Section 5.2.3**, the COVID-19 pandemic caused us to rapidly transfer to remote learning as an alternative to traditional anatomy teaching methods. There were three stages for teaching anatomy during the COVID-19 pandemic. The implementation of the SEP was integrated in the second stage (**Section 5.2.3**) which started in the first term of the academic year 2020/2021. In the second stage, undergraduate medicine anatomy teaching comprised pre-recorded lectures and tutorials, combined within integrated asynchronous remote resources on the MLE. There was no contact teaching. Moreover, Zoom webinars were introduced with a focus on using Complete Anatomy software (3D4Medical, Blackrock, Dublin) (Motsinger, 2020).

A learning activities tutorial guide on the use of the SEP was designed and embedded within the interactive MLE tutorials for Case 2 “Cardiovascular Anatomy” for the first-year medical students (**Group 2**) at Newcastle University in the academic year 2020/2021 (**1MBBS-20/21**) (**Table 5.3**). In addition, we provided detailed content guides and formative assessments to deliver the case learning outcomes. After reviewing the case resources on the MLE, which included Case 2 “Cardiovascular Anatomy” lectures slides and lecture recap, the students were asked to access the SEP learning activity tutorial guide, which was composed of one part. Each student received a username and password via email to access the SEP. Part 1 of the tutorial asked the students to access six different cases in the SEP to identify anatomical features and structures in the thorax region. The tutorial guide also contained a learning activity that asked the participating students to identify features of the thorax cavity in cross-sectional CT scans and then to identify and label these on cross-sectional images included in the guide. Completion of the SEP tutorial guide was optional. At the end of the tutorial, the students were asked to complete an online Likert-type questionnaire with free-text items in order to gather their insights on the use of the SEP. A link to the questionnaire was included in the final section of the tutorial guide. The questionnaire items and the free-text items were similar to the items used in Part 1 (**Section 5.7.2**) (**Table 5.10**), but with a change in the region covered, where, in this part, the students used the SEP to study the thorax.

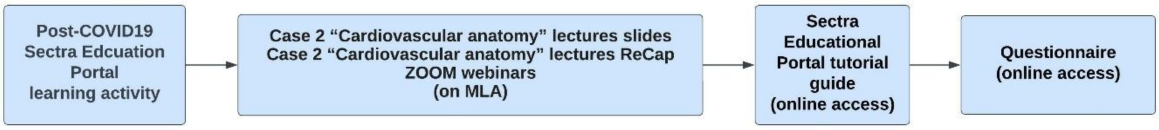


Figure 5.11: Flowchart showing the implementation of SEP learning activities after the COVID-19 pandemic (Part 2).

5.8 Phase IV Methods: Digital Embryology Resources

5.8.1 Study design

Remote 3D digital embryology resources were implemented for first-year medical students (Group 2) **(1MBBS-20/21)** (**Table 5.3**) in the second stage of post-COVID-19 teaching in the first term of the academic year 2020/2021, as described earlier in the chapter (**Section 5.2.3**). Digital embryology resources were introduced to the students as remote resources to address the most demanding and challenging concepts in embryology. Through implementation of digital embryology resources, we aimed to support understanding of the dynamic developmental processes of the embryo when viewing 2D and 3D resources. It is important to note that this was the first remote embryology resource that the first-year medical students experienced and, therefore, it was important to emphasise the shape, size, and structure of the embryos. During the first term of the academic year 2020/2021, core embryology teaching at MSNU was delivered entirely asynchronously.

The digital embryology resources in this project consisted of materials from the HDBR Atlas (Lindsay and Copp, 2005; Kerwin et al., 2010) (http://hdbratlas.org) and the SEP provided interactive digital 3D PDF files (interactive 3D-PDFs) (Academic Medical Centre, Amsterdam, The Netherland).

The HDBR Atlas is an open-source digital atlas that consists of 3D reconstructed digital models of Carnegie stages (CSs) 12 to 23 created using optical projection tomography (Sharpe et al., 2002b; Sharpe, 2003; Kerwin et al., 2010). The 3D models were annotated and linked to anatomical structures. The HDBR Atlas was linked to a database of gene expression collected and developed from the Edinburgh Mouse Atlas Project gene expression database (EMAGE). The HDBR Atlas is part of the HDBR (https://www.hdbr.org) organised by the Institute of Genetic Medicine, Newcastle University, and the Institute of Child Health, University College London (Gerrelli et al., 2015). The HDBR is a tissue bank that collects human embryonic and foetal tissues ranging from 3 to 20 weeks of development for research purposes (Lindsay and Copp, 2005). The digital atlas and the gene expression data obtained from the HDBR materials were brought together on the HuDSeN human gene expression spatial database (http://www.hudsen.org) (Kerwin et al., 2010) to form the HuDSeN Electronic Atlas of the Developing Human and HuDSeN Human Gene Expression Spatial Database.

The Sectra subscription allowed the MSNU to download interactive 3D embryology PDF files. These interactive 3D-PDF materials were based on the 3D Atlas of Human Embryology (https://www.3dembryoatlas.com) created by embryologists and students at the Department of Anatomy, Embryology and Physiology of the Academic Medical Centre in Amsterdam, Netherlands (de Bakker et al., 2012). The atlas is available to facilitate embryology education, learning, and research for the scientific community. The 3D Atlas of Human Embryology contains 14 real human embryo cases between CS 7 and CS 23 (15–60 days). The atlas consists of digital stacks of histological sections of embryos, digital stacks for 3D rendering, and interactive and user-friendly 3D-PDFs of all organ systems (de Bakker et al., 2012). The interactive 3D-PDFs present interactive 3D models of the embryo to allow the user to explore and understand the 3D representation, the location of the embryo, and the organs in relation to other organs. Only the interactive 3D-PDF files were used in the study, and the students were provided with user instructions.

The digital embryology resources included the integration of learning activities involving the HDBR Atlas and SEP interactive 3D-PDF files, which were embedded within an interactive MLE tutorial for Case 2 "Embryology of the Heart". In addition, we provided detailed content guides within these resources to support the delivery of learning outcomes for the curriculum. The designed learning activities (**Appendix**) supported the learning outcome of the case. Students were asked to access the learning activity guide after reviewing the case resources on the MLE. These included Case 2 embryology lecture slides, Case 2 embryology lecture recap, and a Case 2 embryology timeline slide. A tutorial guide with materials from the HDBR Atlas (http://hdbratlas.org) and the interactive 3D-PDF files was utilised. The guide was made up of three parts. Part 1 included access to the 3D model section on the HDBR Atlas page to understand the development of the heart from week 4 to week 8. The steps can be checked in the tutorial in the **appendix**. Part 2 involved interaction with 3D models of the heart. At first, the students were asked to access the cardiovascular system section of the HDBR Atlas page, which directed them to 3D models of the heart, giving them access to 3D digital models of the cardiovascular system of the embryo at different CSs. The page consisted of two sets of movies to illustrate the development of the heart from CS 12 (week 4), CS 13 (week 4), CS 14 (week 5), CS 15 (week 5), and CS 16 (week 6).

The movies are arranged in two rows, of which the top row shows the painted hearts, while the bottom row shows the heart within the body. The second step involved the use of 14 interactive 3D-PDF files consisting of 3D models of the embryo from CS 7 to CS 23. These were attached to the tutorial to allow the students to navigate the different CSs through three dimensional models. The third part included a spotter activity in which the students had to identify different CSs and to name the highlighted structures. The answers for the identification activity were provided to the students in the same tutorial.

After completing the cardiovascular embryology activities, the first-year medical students completed an online Likert-type (**Table 5.11**) and free-text questionnaire. The free-text items included:

- *Please describe why your interactions with the HDBR digital heart models were/were not important in improving your understanding of 3D and cross-sectional anatomical features of the heart.*
- *Please describe why your interactions with the interactive 3D-PDFs of the heart were/were not important in improving your understanding of 3D and cross-sectional anatomical features of the heart.*
- *Please describe any OTHER resources you used with* **Digital Embryology Resources** *(HDBR digital heart models & interactive 3D-PDFs) in order to complete any part of the activities in the Case 2 Cardiovascular Embryology MLE tutorial.*
- *Please describe any other suggestions you may have for improving how can we use the* **Digital Embryology Resources** *(HDBR digital heart models & interactive 3D-PDFs) in the future*.

As described earlier in this chapter, these data were then analysed statistically and by semi-quantitative content analysis to identify students' perceptions of interacting with digital embryology resources. Four students out of the total cohort remotely participated in a focus group via video-call. The focus group was recorded and transcribed verbatim to perform a thematic analysis, as described in **Sections 5.3.5**, **5.3.9**, **5.5.7**, and **5.5.8**.

Questionnaire item	Seven-point Likert-type scale range
1. The Digital Embryology Resources (HDBR digital heart models & interactive 3D-PDFs) improved my understanding of the embryology of the heart.	1 = strongly disagree 7 = strongly agree
2.The ability to actively interact with and manipulate the Digital Embryology Resource (HDBR digital heart models & interactive 3D-PDFs) images was important for improving my interpretation of the 3D embryology features in cross-sectional images.	1 = strongly disagree 7 = strongly agree
3. Digital Embryology Resources (HDBR digital heart models & interactive 3D-PDFs) are a valuable self-directed learning resource for studying the 3D aspects of the embryology of the heart and I wish to use DIGITAL EMBRYOLOGY RESOURCES for studying embryology again in the future.	1 = strongly disagree 7 = strongly agree
4. The Case 2 Cardiovascular Embryology MLE tutorial was a valuable self-directed learning resource for studying the 3D aspects of the embryology of the heart.	1 = strongly disagree 7 = strongly agree
5. I would recommend Digital Embryology Resources (HDBR digital heart models & interactive 3D-PDFs) and the case activities to other medical students for their embryology learning.	1 = strongly disagree 7 = strongly agree

Table 5.11: Questionnaire items on digital embryology resource use in the form of seven-point Likert-type scales.

5.9 Ethical Assessment

5.9.1 Ethical approval

At Newcastle University, researchers must obtain ethical approval from the Faculty of Medical Sciences Ethics Committees before any research is carried out, including any research involving human participation.

Before the research activities or studies were conducted, an ethical proposal was submitted on 21 November 2017 for review by the Faculty of Medical Education Ethics Committee. All study details were explained in the proposal, including the project aims, project design, research methods, participant details, participant consent form (**Appendix**), participant debriefing (**Appendix**), and measures to protect participants' confidentiality. After submission, specific amendments were made based on ethics committee recommendations.

5.9.2 Consent forms, and student participation and information

The students were invited to participate through in-person announcements made by the researcher at the end of anatomy lectures, because the use of email to invite the students was not permitted by the gatekeeper. Written and verbal information and explanations were provided to all students before the start of research activities, per ethics committee and/or Research Management Group (RMG) requirements. A debriefing information sheet was given to all students at the beginning of each research study in accordance with the requirements for ethical approval. The participating students gave written consent to participate in the study. All participants who consented to participate in the research were able to participate in optional or timetabled practical sessions, depending on the degree programme requirements. The participants were informed that by participating in the questionnaires, test questions, and focus groups, they agreed that the data from their responses could be used for research, dissertation, publication, and doctoral thesis purposes. The participating students were given 10 minutes to answer all questions and return the questionnaire. By submitting the questionnaire, the students gave consent to use the collected data for publication and PhD dissertation purposes. All participants in the focus groups provided a signed consent form agreeing to recording of the interview and the use of the analysed data in publications and a PhD dissertation. The practical research sessions occurred during some timetabled sessions and some optional practical sessions, but participation was completely optional. The participating students were given the choice to withdraw at any time from any research activity by not answering any questions in the questionnaire or the tests, or by leaving the research portion of the practical session or the focus group whenever they wished. All information gathered from the participants' answers to the experimental tests (pre, post, and delayed), questionnaires, and focus group questions, and the research results, were kept anonymous and confidential. Throughout the research, the students' ID numbers were used as participant numbers instead of the students' names, so that the studies would not be able to identify the students by name, and the confidentiality of the students' identities was ensured. The students were assured that when the research was published or submitted as a dissertation, they would not be identified by name or student ID number.

5.9.3 Research management group and gatekeeper approval

After ethical approval, a research proposal template was submitted to the Newcastle University School of Medical Education RMG to allow research activities to proceed. The aims, research questions, and methods were described in the templates. The project was anticipated to involve the participation of undergraduate and postgraduate students currently taught within the Anatomy and Clinical Skills Centre. Participants were likely to be undergraduate MBBS students, but also accelerated MBBS, PA, FRCR radiology, MRes surgical anatomy, and MSc clinical science students, and potentially those from other degree programmes within Faculty of Medical Sciences (FMS), including biomedical science and dentistry, could be included. The research proposal template indicated that the participation of students in the research would not occur during timetabled sessions and would occur only during optional non-timetabled extra-curricular sessions or activities. It specified that recruitment of MBBS students would follow MBBS gatekeeper guidelines on student recruitment. According to gatekeeper regulations, students can be recruited through mention of the study during teaching, but the use of email to recruit for any research activity is not permitted. The students' participation in any aspect of the research was voluntary and optional, and written informed consent was required from all participants. On 22 January 2018, the project "**Digital and 3D approaches for enhancing human anatomy education**" was approved by the RMG. This approval allowed the research activities to proceed. After receiving clarifications from the ethics committee, final ethical approval for project 1431/2095/2018 was obtained by the Faculty of Medical Sciences Ethical Review Committee on 10 January 2018. The approval letter is provided in the Appendix.

5.9.4 Amendment of the ethical approval

Because of the COVID-19 pandemic, an amendment was requested to extend the end date for the ethics approval. Previously, the committee approved the project from 10 January 2018 to 9 October 2020. An additional three months was necessary to complete the final portions of the research activities and the data collection. Due to the COVID-19 outbreak, all research and data collection were performed remotely (via online learning resources, online questionnaires, Zoom focus groups, etc.). Student participation information and consent forms were provided remotely through electronic means, such as emails. Researchers or participants incurred no health or safety risks with respect to COVID-19, because all research activities were online and occurred via remote resources. No direct contact occurred between the researcher and participants. The amendment application was approved, and a new end-date of 9 January 2021 was set.

Chapter 6. Results

6.1 Phase I: Investigating Challenging Topics in Anatomy Education

In this section of the results, the challenging topics and areas faced by medical students when studying anatomy were investigated. This was the first part of a study that involved the analysis of a Likert-type questionnaire followed by focus group analysis to obtain student insights regarding challenging areas and topics in anatomy. Based on the reviews conducted in Chapter 4 (**Section 4.1**), the concepts that were likely to be challenging for new medical students included clinical-image interpretation and embryology, among others.

6.1.1 Pilot study: Medical students' perceptions of challenging topics in anatomy learning

In 2017, medical students pursuing the Accelerated Bachelor of Medicine and Surgery (MBBS) Programme at Newcastle University (n = 17) (**Table 5.3**) participated in a pilot study aimed at validating the challenging topics questionnaire (**Table 5.4**). The questionnaire was validated by a Cronbach alpha value of 0.9, where the acceptable range is from 0.7 to 0.9 (Tavakol and Dennick, 2011).

6.1.2 Medical students' perceptions of challenging topics in anatomy learning

In the 2017/2018 academic year, the questionnaire participants were second-year medical students (MBBS) (n = 95) (**Table 5.3**). Medical students at this stage have completed lecture-based and practical learning of clinical and basic relevance, including learning about the lower limbs, upper limbs, thorax, abdomen, and head and neck. Gender demographics showed that the responding population sample consisted of female (n = 55, 58%) and male (n = 40, 42%) participants. The questionnaire included items to identify the challenging topics and areas that the students found most difficult. A mean value > 4 with a response rate > 50% for each questionnaire item was considered to indicate an overall challenging topic or overall agreement, while a mean value < 4 with a response rate < 50% for any questionnaire item was considered to indicate a non-challenging topic or overall disagreement. Based on the mean values and response rates for the seven-point Likert-type scale (**Figure 6.1**), embryology was perceived as the most challenging topic, with a high level of significance ($P < 0.001$). The second most challenging topic (**Figure 6.1**) was histology, followed by microanatomy. Both histology and microanatomy are anatomy topics, and both are covered in the anatomy lectures. The mean values for all items (**Figure 6.1)** indicated that all topics were considered to be challenging, but the level of difficulty varied from one topic to another. Friedman's test showed a highly significant difference in the level of difficulty between the five anatomical topics (**Figure 6.1)** (χ^2 = 92.9, P < 0.001, w = 0.245). Pairwise comparison showed that embryology was much more challenging than clinical images, microanatomy, and gross anatomy (P < 0.001). Having identified the most difficult area of anatomy learning, the next step was to investigate the students' perceptions of the most challenging anatomical regions. Among the participating students, 78% (n = 74) considered the head and neck to be the most challenging anatomical region (mean = 5.35, SD ± 1.94, response rate = 78%) **(Figure 6.2)**. Friedman's test showed a highly significant difference in the level of difficulty between distinct anatomical regions (χ^2 = 113.1, P < 0.001, w = 0.298). Pairwise comparison showed that the head and neck was the most challenging region among all anatomical regions (P < 0.001). The pelvis and perineum (n = 51, 54%), limbs (n = 48, 51%), and abdomen (n = 39, 41%) were identified as challenging topics, with mean values exceeding 4. The thorax was not considered to be challenging, with a mean value of 3.99 (SD ± 1.29), and a smaller proportion of students (n = 27, 28%) perceived the thorax as a challenging anatomical region (**Figure 6.2**).

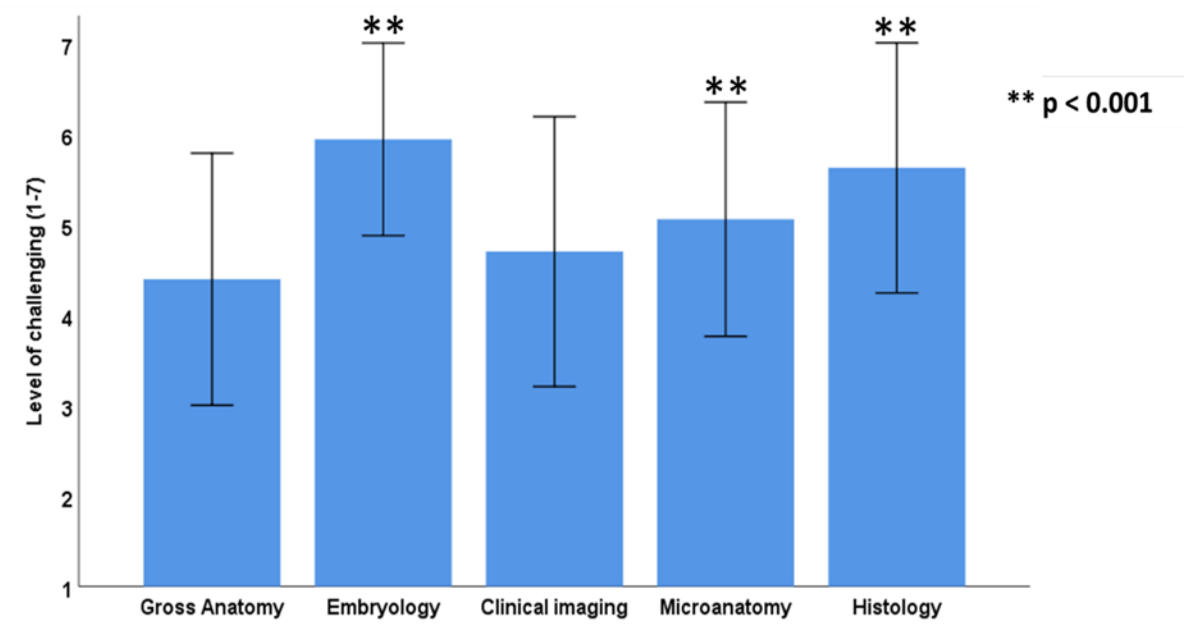


Figure 6.1. Students' perceptions of challenging topics in anatomy learning (n = 95). Embryology was considered to be the most challenging topic (mean = 5.95, SD ± 1.07, response rate = 89%, n = 85). At a high level of significance, embryology was perceived as more challenging (**P < 0.001) than clinical images, microanatomy, and gross anatomy. Student responses to Likert-type scale items showed a highly significant difference (**P < 0.001) between student perceptions of histology (mean = 5.63, SD ± 1.38, response rate = 80%), gross anatomy (mean = 4.40, SD ± 1.39, 53%), and clinical imaging (mean = 4.71, SD ± 1.49, 63%) in terms of difficulty levels. Pairwise comparison showed a highly significant difference in the level of difficulty (**P < 0.001) perceived for microanatomy alone (mean = 5.06, SD ± 1.29) and gross anatomy (mean = 4.40, SD ± 1.39). A mean score > 4 with a response rate > 50% indicates that an anatomical topic is challenging for the cohort overall, where 1 = not challenging at all, 7 = extremely challenging.

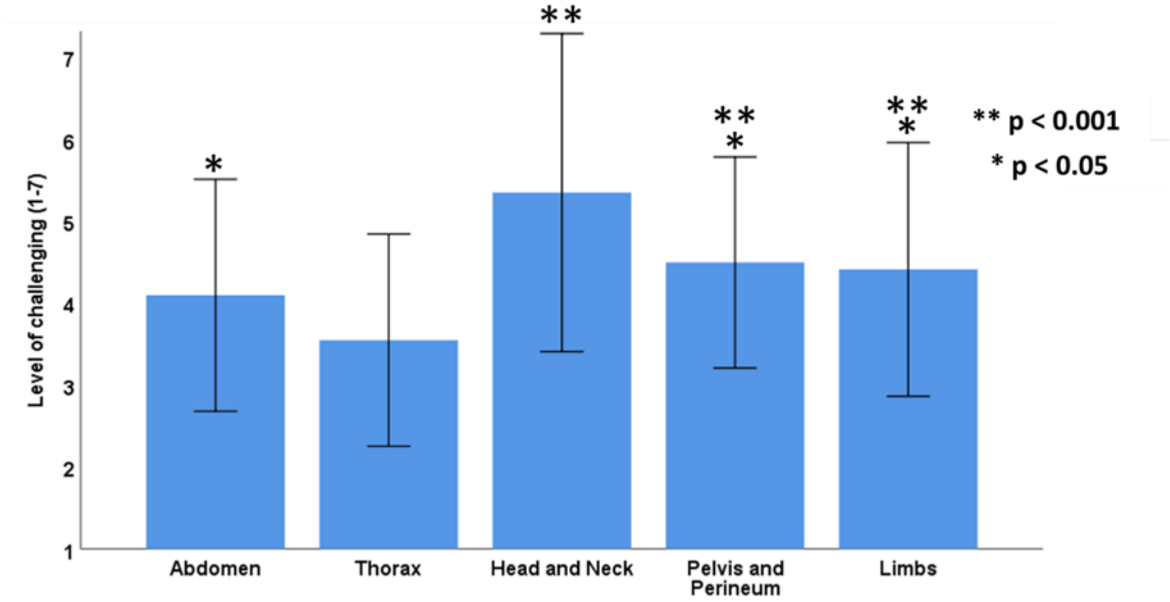


Figure 6.2. Students' perceptions of challenging anatomical regions in anatomy learning (n = 95).

Friedman's test showed a highly significant difference in difficulty levels between different anatomical regions (χ^2 = 113.1, P < 0.001, w = 0.298). Head and neck was considered to be the most challenging topic (mean = 5.35, SD ± 1.94). Pairwise comparison showed that the head and neck was the most challenging region among all anatomical regions (**P < 0.001). There was a highly significant difference (*P < 0.001) in perceived difficulty levels between the pelvis and perineum alone (mean = 4.49, SD ± 1.29, 54%) and the thorax (mean = 3.55, SD ± 1.29, 28%) and a significant difference (*P < 0.05) for the abdomen region (mean = 4.09, SD ± 1.41, 41%). Friedman's test showed a highly significant difference in perceived difficulty level between the limbs and the thorax (**P < 0.001) and a significant difference for the abdomen (*P < 0.05). Pairwise comparison showed that the abdomen is significantly more challenging than the thorax (*P < 0.05). A mean score > 4 with a response rate > 50% for each item indicates that an anatomical region is challenging for the cohort to understand overall, where 1 = not challenging at all, 7 = extremely challenging.

The brain was perceived as the most challenging organ to understand, with an 81% response rate (n = 77) from the participants (mean = 5.64, SD ± 1.44) (**Figure 6.3**). Friedman test analysis showed that the student responses for this item exhibited a highly significant difference (χ^2 = 215, P < 0.001, w = 0.378) from all other items. The mean values for all other organs were < 4, indicating that these visceral organs were not difficult to understand (**Figure 6.3**).

The results show that the pericardial sac (mean = 4.64, SD ± 1.28, n = 57, 65%), pleural cavity (mean = 4.9, SD ± 1.41, n = 51, 54%), peritoneum (mean = 5.20, SD ± 1.41, n = 71, 75%), and inguinal canal (mean = 4.63, SD ± 1.31, n = 53, 56%) were considered to be challenging features by the respondents (**Figure 6.4**). Among these topics, the peritoneum and its boundaries and reflections were considered to be the most challenging (**Figure 6.4**).

Students were asked to rank the level of difficulty when attempting to understand the following anatomical structures: fascia, muscles and tendons, bones and ligaments, visceral organs, blood vessels, and nerves and plexuses (**Figure 6.5**). Bones, ligaments, and organs were not challenging for the students, whereas all of the other topics were considered to be challenging (**Figure 6.5**). The responses for the nerves and plexuses were significantly different (**P < 0.001) from the responses for the other gross structures, indicating that the nerves and plexuses were most challenging topic among these anatomical structures.

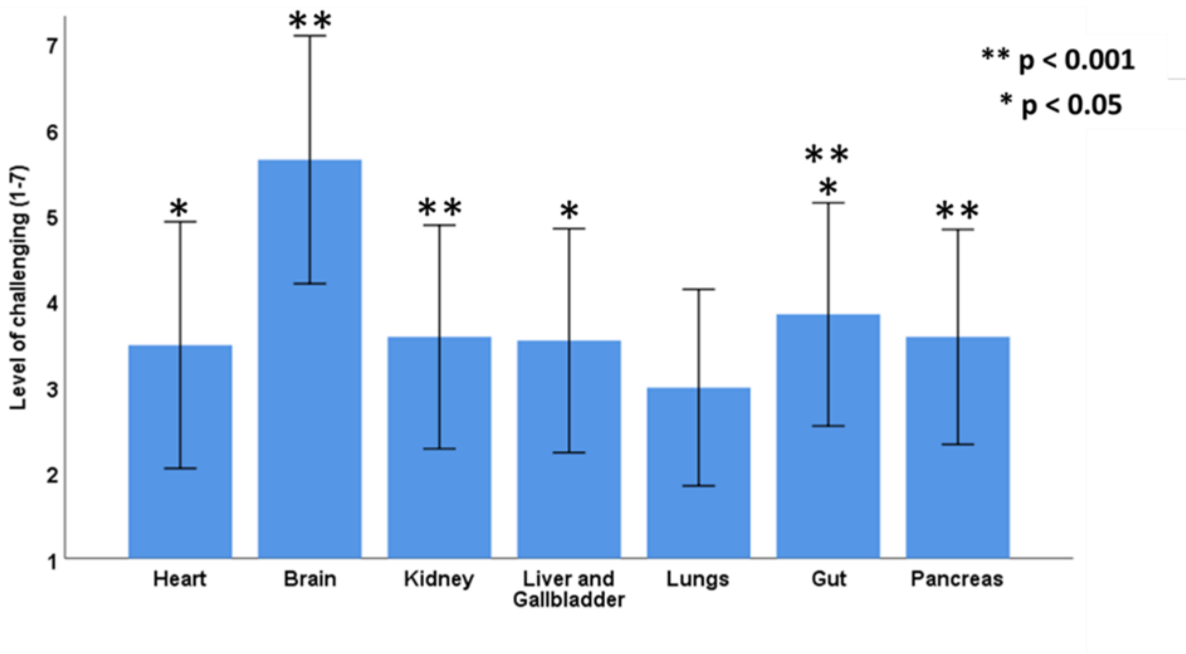


Figure 6.3. Students' perceptions of visceral organs (n = 95).

Friedman's test showed a highly significant difference in the complexity level of understanding different anatomical organs ($\chi^2 = 215$, P < 0.001, w = 0.378). The brain was considered to be the most challenging organ (mean = 5.64, SD ± 1.44, **P < 0.001) among the anatomical organs. The gut is more challenging than the lungs (**P < 0.001) at a high level of significance and significantly more challenging than the heart (*P < 0.05). Student responses to the Likert-type scale items for the other organs gave mean values < 4, indicating that the students did not find the other organs challenging. Mean item scores > 4 and response rates > 50% for each item indicate that a visceral organ is challenging for the cohort overall, where 1 = not challenging at all, 7 = extremely challenging.

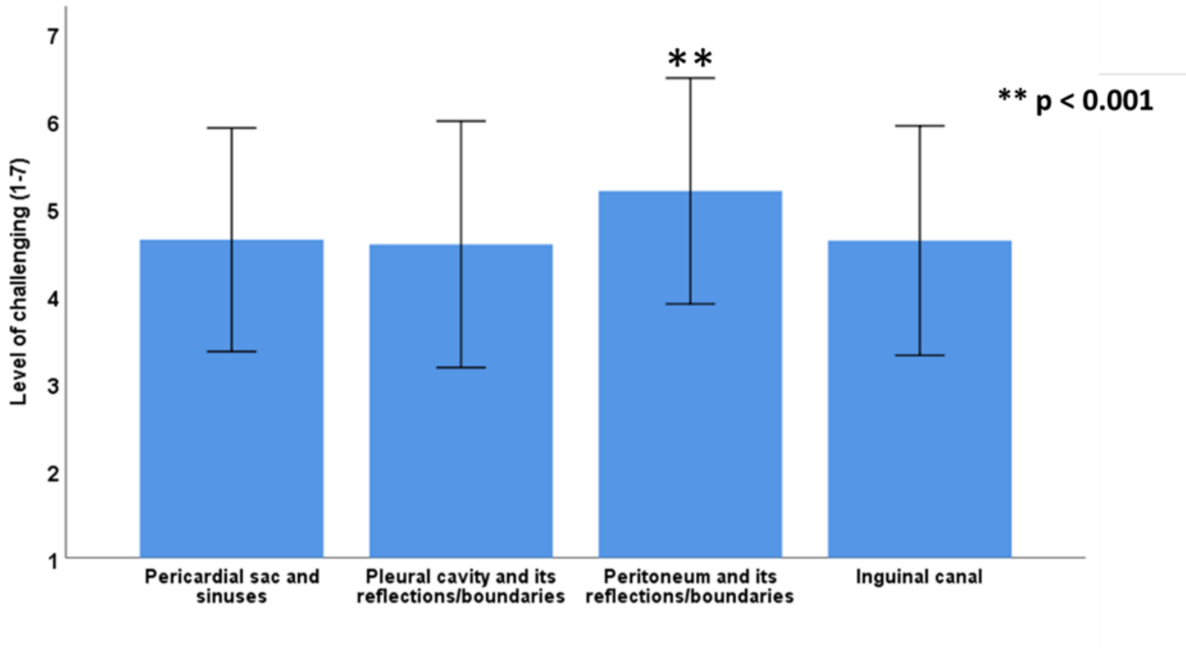


Figure 6.4. Students' perceptions and insights regarding challenging features in anatomy (n = 95).

The peritoneum was considered to be the most challenging anatomical feature (mean = 5.2, SD ± 1.29). The peritoneum was perceived as more challenging (**P < 0.001) than the pericardial sac, pleura cavity, and inguinal canal at a high level of significance. Mean item scores > 4 with > 50% response rates for each item indicate that an anatomical feature is challenging for the cohort overall, where 1 = not challenging at all, 7 = extremely challenging.

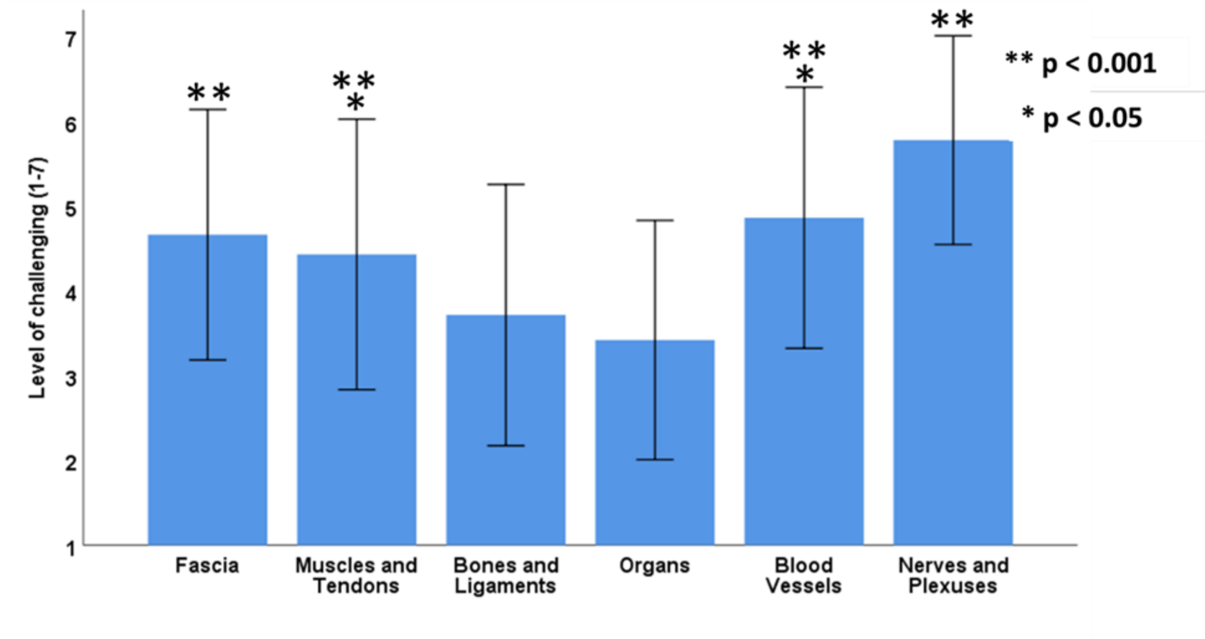


Figure 6.5. Student perceptions and insights regarding challenging structures in anatomy (n = 95).

Friedman's test showed a highly significant difference in the difficulty levels for understanding different anatomical organs (χ^2= 186.9, p < 0.001, w = 0.39).

The nerves and nerve plexuses were considered to be the most challenging topic (mean = 5.78, SD ± 1.23, 85%). At a high level of significance, the nerves and plexuses were perceived as more challenging (**P < 0.001) than all of the other anatomical structures mentioned in that item. Student responses to the Likert-type scale items show a highly significant difference (**P < 0.001) for student perceptions of blood vessels (mean = 4.86, SD ± 1.54, 67%) compared with bones and ligaments (mean = 3.72, SD ± 1.54, 33%) and organs (mean = 3.42, SD ± 1.41, 26%) and a significant difference for muscles and tendons (mean= 4.4, SD ± 1.6, 48%) (*P < 0.05) in terms of their difficulty level. There was a highly significant difference in difficulty (**P < 0.001) between student perceptions of the fascia alone (mean = 4.66, SD ± 1.48, 57%) and the bones and ligaments and organs. Muscles and tendons exhibited a highly significant difference in difficulty level (**P < 0.001) from the organs and a significant difference from the bones and ligaments (*P < 0.05).

The mean values for the bones and ligaments and organs were < 4, indicating that those structures were not challenging to the students. A mean score > 4 with > 50% responses indicates that an anatomical region is challenging for the cohort to understand overall, where 1 = not challenging at all, 7 = extremely challenging.

6.1.3 Anatomy and cross-sectional images

Thus far, the results have shown that clinical imaging is challenging for students (**Figure 6.1**). In this section of the questionnaire (**Table 5.4**), the second-year medical students were asked to provide their perceptions of interpreting specific anatomical features that were covered in the anatomy curriculum in clinical cross-sectional images. The students reported that interpreting muscle compartment anatomy in cross-sectional images was the most challenging task (**Figure 6.6**). The abdomen and heart were considered the second-most challenging areas of clinical imaging. Most of the participants found that the liver was not a challenging area to identify or interpret in clinical cross-sectional images (**Figure 6.6**).

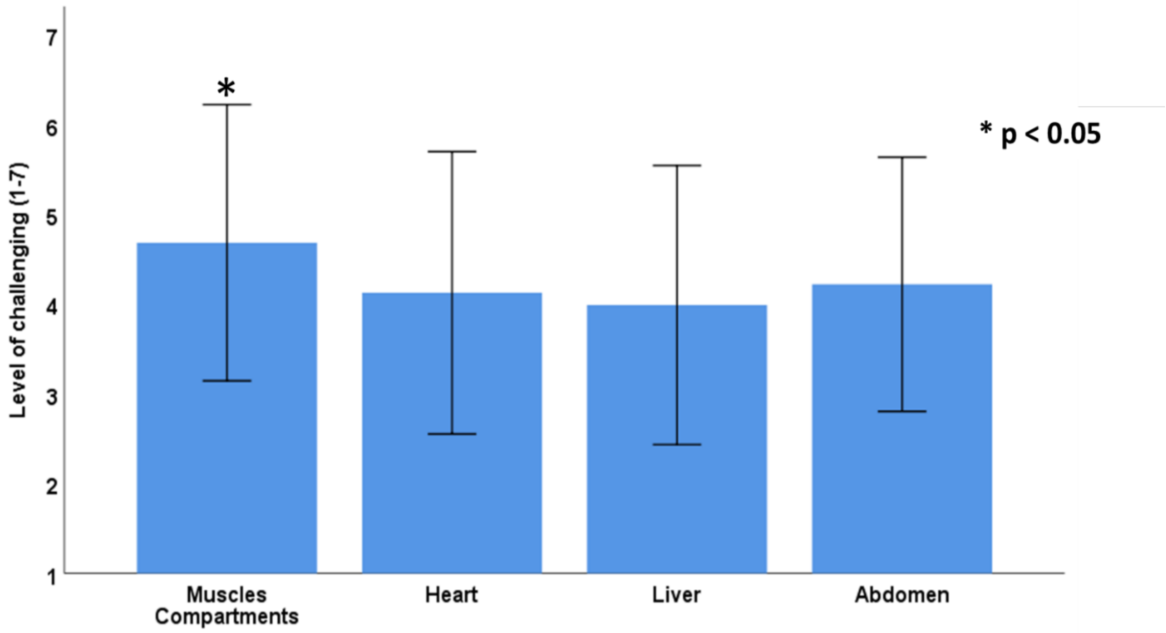


Figure 6.6. Anatomical features in clinical cross-sectional images (n = 95).
The muscle compartments were considered to be the most challenging structures to identify in cross-sectional images (mean = 4.68, SD ± 1.54). Among the participants, 54 (57%) perceived the muscle compartments as significantly more challenging to interpret (*P < 0.05) than the heart and liver. Student responses to Likert-type scale items showed difficulty in identifying the heart (mean = 4.13, SD ± 1.57) and abdomen (mean = 4.22, SD ± 1.42) in cross-sectional images. The students found it less challenging to identify the liver (mean = 3.99, SD ± 1.55, 36%) in cross-sectional images. A mean score > 4 with a response rate > 50% indicates that an anatomical feature is challenging for the cohort to understand overall, where 1 = not challenging at all, 7 = extremely challenging.

6.1.4 Factors behind the challenging concepts in anatomy

With a mean value of 5.74 (SD ± 1.32), Friedman's test showed that the perception of difficulty in anatomy learning due to the volume of content that must be learned was significantly higher when compared with all other reasons (P < 0.001) (**Figure 6.7**). Interpretation of 3D anatomical features in 2D images and 3D spatial relationships of anatomical structures were also considered as factors that made anatomy learning challenging (**Figure 6.7**). The participants' responses to the other factors (lack of resources, anatomical terminology, teaching contact time) resulted in mean values below 4 (**Figure 6.7**), indicating an overall disagreement regarding whether these factors were related to the challenges of learning anatomy.

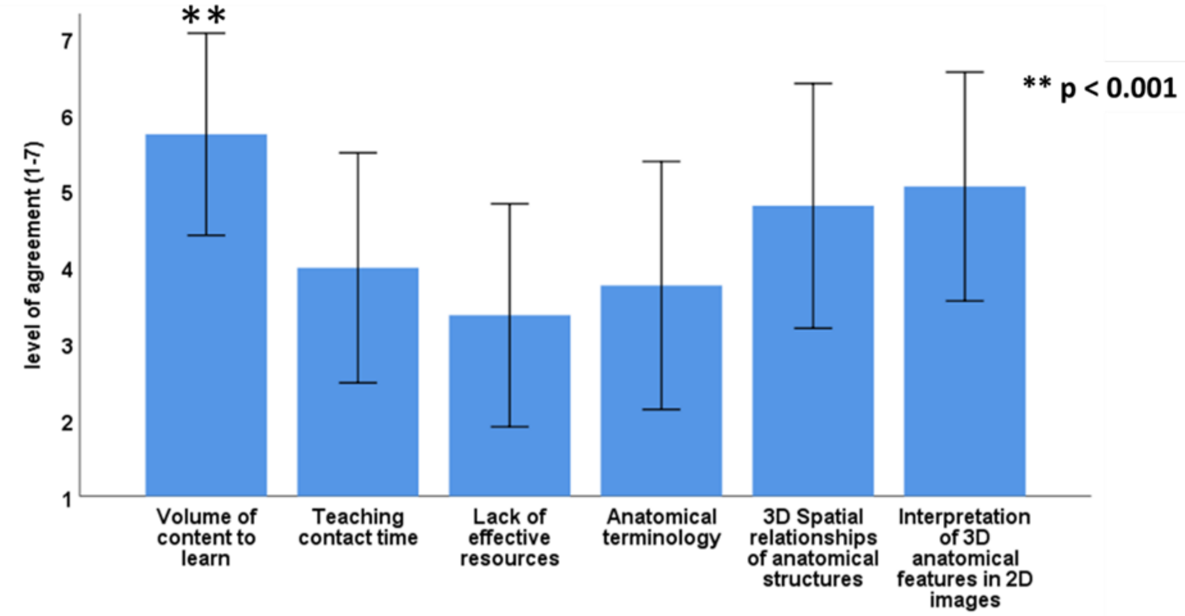


Figure 6.7. Students' perceptions of challenges in anatomy learning.
Student responses to this item showed an overall agreement among student perceptions that the volume of content (mean = 5.74, SD ± 1.32, 84%), interpretation of 3D anatomical features in 2D images (mean = 5.05, SD ± 1.5, 72%), and 3D spatial relationships of structures (mean = 4.8, SD ± 1.6, 65%) were the main factors behind the challenges of learning anatomy. The volume of content alone was considered as the most significant reason that anatomy is challenging, with the responses showing a highly significant difference (**P < 0.001) from the other factors. Most of the student responses showed that teaching contact time (mean = 3.99, SD ± 1.51), anatomical terminology (mean = 3,76, SD ± 1.62), and lack of effective resources (mean = 3.37, SD ± 1.46) were not factors behind the challenges of learning anatomy.

6.1.5 Skills needed to learn anatomy

The results showed that all participants had similar perceptions with respect to the skills needed to learn anatomy (**Figure 6.8**). The mean values of the student responses indicated an overall agreement that spatial ability, visual observation, haptic observation (touch), knowledge retention (memory), and understanding of different anatomical structures were needed to enhance learning of human anatomy.

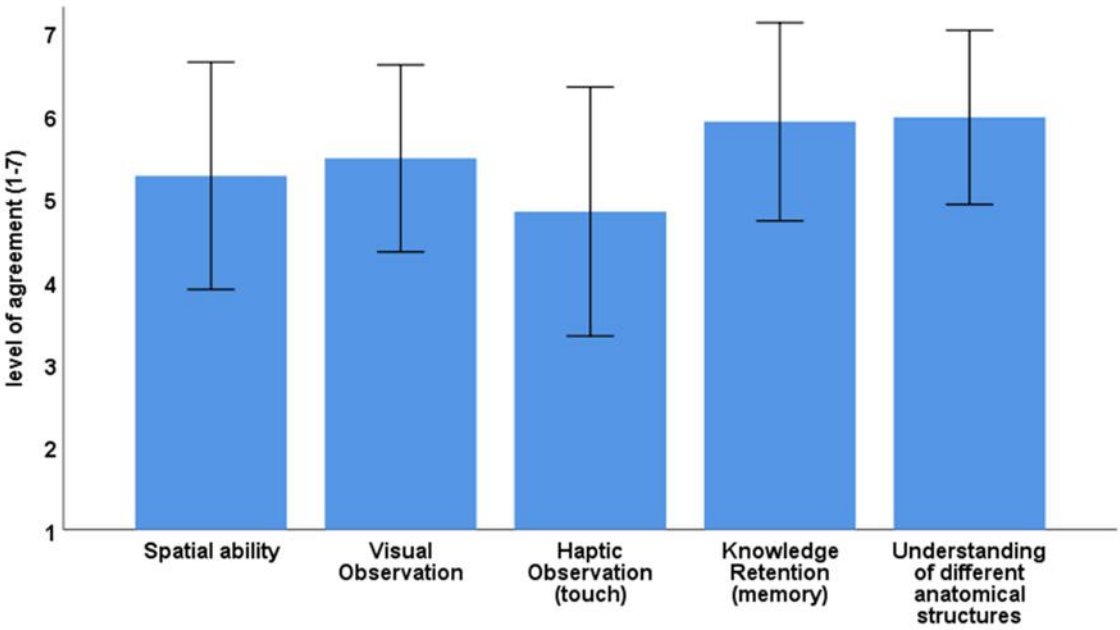


Figure 6.8. Skills needed to learn anatomy.
A mean score > 4 with a response rate > 50% of participants indicates overall agreement. Student responses to this item showed overall agreement that all of the mentioned skills were needed to enhance anatomy learning. The understanding of different anatomical structures (mean = 5.98, SD ± 1.05, 92%) was considered to be the most important skill needed in learning anatomy.

6.1.6 Student perceptions of self- directed resources to enhance anatomy learning

Second-year medical students (MBBS) were asked to provide their insights into the added value of self-directed learning resources. Students responded to seven-point Likert-type items, and responses to items were analysed statistically. A mean value > 4 for each item was considered to indicate overall agreement, while a value < 4 was considered to indicate overall disagreement (**Figure 6.9**). Students reported that two of the self-directed resources mentioned in the questionnaire (Sectra, 3DP models) added great value for learning anatomy. Having shown the importance of self-directed learning resources (**Figure 6.9**), it was important to assess student perceptions of new self-directed learning resources. Themes arising from semi-quantitative thematic content analysis of free-text comments indicated that students (n = 16, 50%) would welcome additional online interactive resources; moreover, five students (16%) would welcome 3DP models **(Figure 6.10)**.

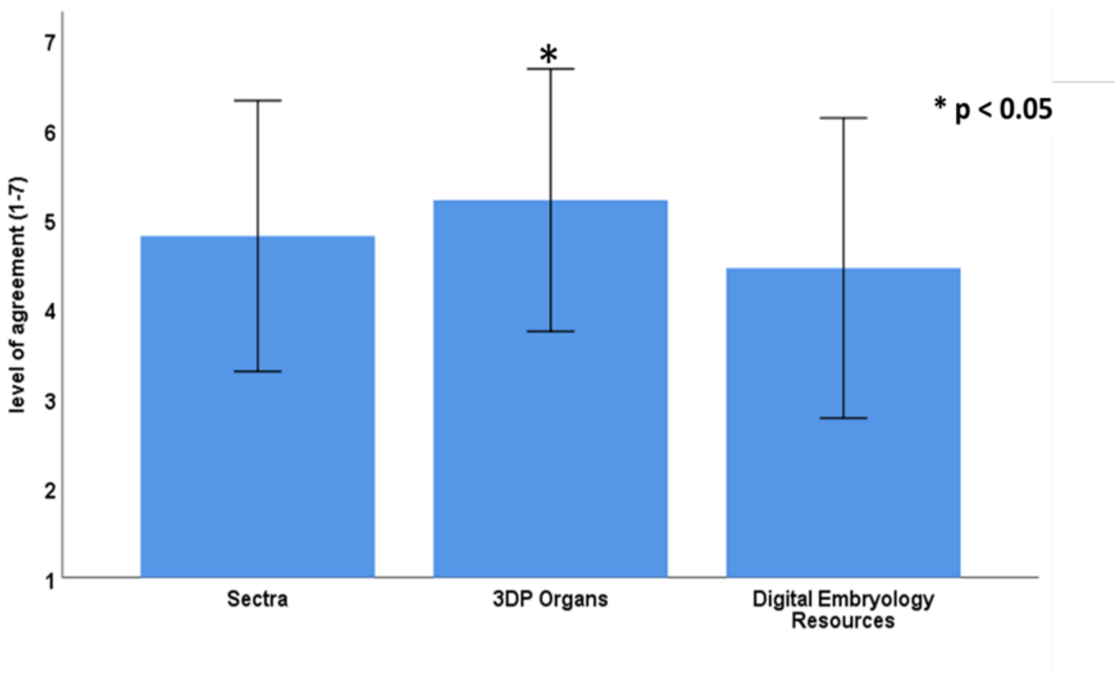


Figure 6.9. Added value of self-directed learning resources.
Student responses to Likert-type scale items show an overall agreement among the added value of Sectra and 3DP organs and digital embryology resources as sources for self-directed learning. 3DP models alone (mean = 5.21, SD ± 1.47, 68%) were perceived as significantly more valuable (*P < 0.05) than digital embryology resources (mean = 4.45, SD ± 1.67) as a source of self-directed anatomy learning. A mean score > 4 with a response rate > 50% indicates overall agreement with the statements by the cohort, where 1 = strongly disagree, 7 = strongly agree.

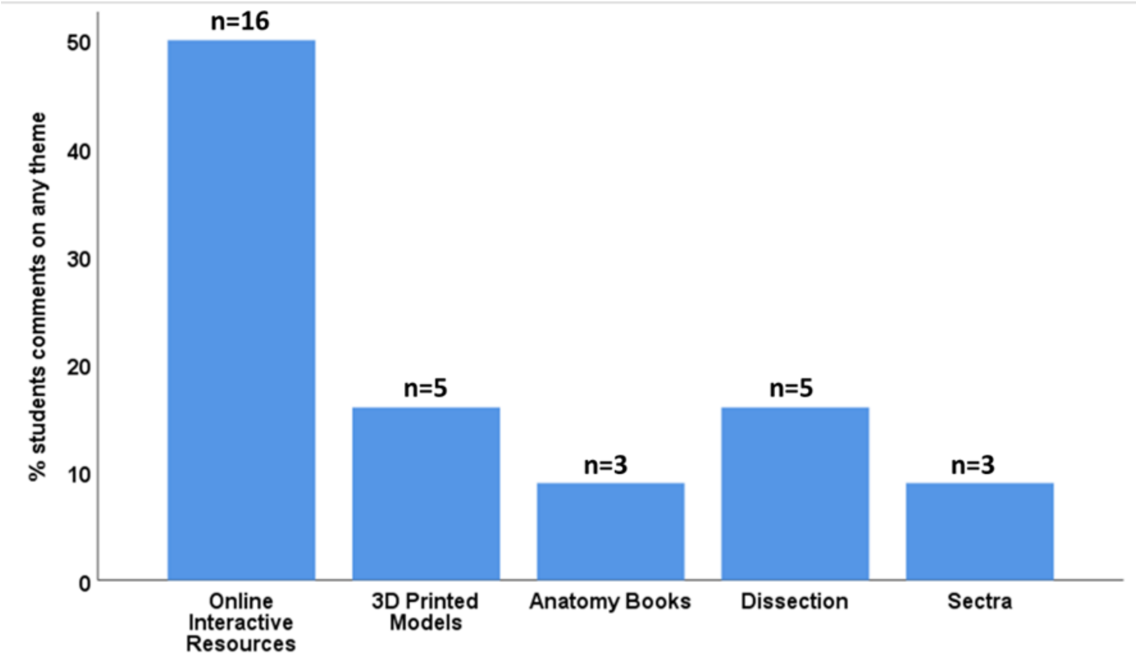


Figure 6.10. Perceived student requirements for self-directed anatomy learning resources. Semi-quantitative thematic content analysis of responses (n = 32) to the following free-text questionnaire item: *Please describe any taught or self-directed resources that would enhance your anatomy learning*. A majority of participants (50%) indicated that they needed more online interactive resources to enhance their anatomy learning.

6.1.7 Student perceptions of challenging areas in interpreting cross-sectional clinical images

Further analysis was performed to analyse themes arising from the students' comments regarding the major reasons causing clinical and cross-sectional image interpretation to be difficult and the most challenging body regions to identify in clinical images (**Figure 6.11**).

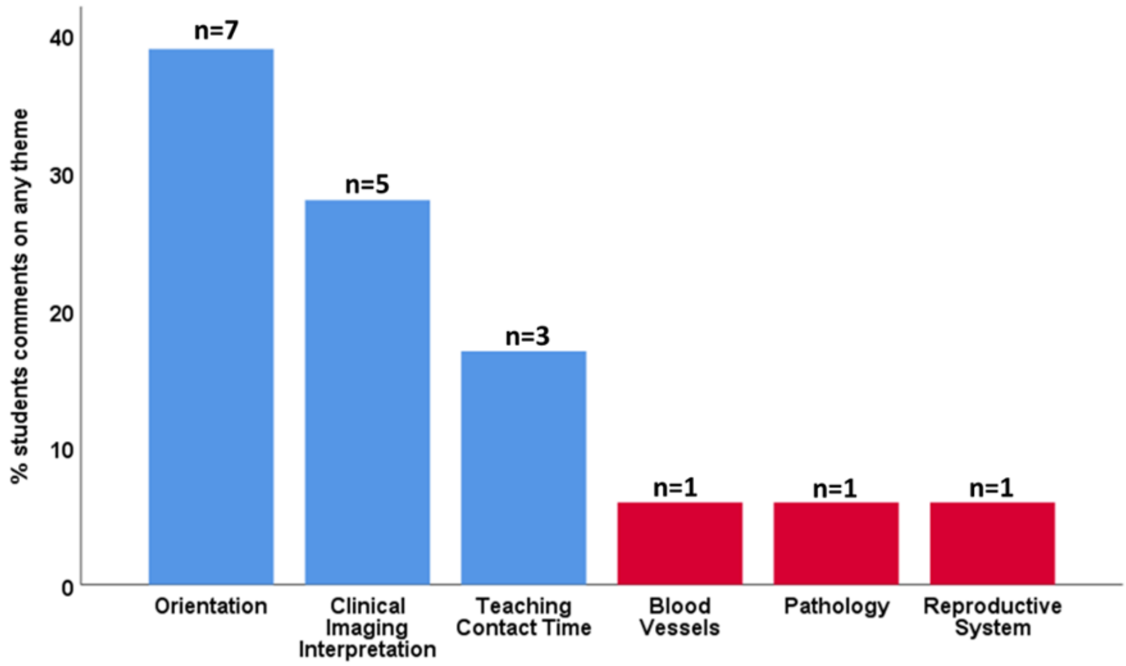


Figure 6.11. Perceived challenges among concepts and topics in interpreting cross-sectional images.
Themes arising from semi-quantitative thematic content analysis of the participating students' responses (n = 18) regarding challenging concepts (blue bars) and challenging topics (red bars) when attempting to interpret and understand anatomical features and structures in cross-sectional clinical images.

6.1.8 Concepts and themes arising from focus group analysis

Having utilised an objective data collection approach to identify the specific nature of student perceptions, a focus group was formed during the 2017/18 academic year to obtain deeper and richer student insights with respect to the difficulties faced by students when studying anatomy. The focus group (n = 4) consisted of Accelerated MBBS Programme students (n = 3) and second-year (MBBS) (n = 1) students (**Table 5.3**). Participating students were asked to respond to and discuss questions asked by the moderator. The discussion was recorded, and after the discussion, the recording was transcribed for analysis and evaluation. From the focus group data, three main themes emerged through double-coded qualitative thematic analysis.

Theme 1: 3D and complexity of anatomy learning

Embryology was identified as a complex topic, mainly when using 2D resources. Student participants also reported that they found some visceral organs challenging to understand. The brain was considered to be the most challenging of the viscera to study and understand by the participants. Students also reported that the kidneys and spinal cord were hard to understand when learning anatomy:

"*Embryology is always on the screen and is always in 2D, and so obviously you can't have embryology prosection but having something that is 3D-printed would be really helpful with embryology learning."* (Participant C)

"If you had me label the brain right now, I would do very badly I think. We have been taught a lot about it, but other organs stick in my mind a little better." (Participant A)

"One of the troubles that I had when I did kidney physiology was to have a full understanding of the concept of nephrons within the kidneys and how everything is recycled within the kidney . . . all these points become fuzzy when it comes to understanding the anatomy of the kidneys and how nephrons fit in to that anatomy." (Participant B)

"I think we need teaching around the spinal cord." (Participant D)

"*I find it more difficult not necessarily thinking about where things are and identifying where everything is than identifying pathology in a CT [computed tomography scan].*" (Participant C)

"*I totally agree, I think when it comes to pathology beyond our expertise, we cannot really familiarise yourself on what's normal.*" (Participant B)

"I think going back to do a revision is difficult." (Participant A)

"I think it is different when you are in an accelerated course because there is no time to do anything." (Participant B)

Theme 2: Spatial awareness and memorisation

The participants agreed that spatial awareness and memorisation are essential skills for understanding anatomy and making the connection with all the anatomical structures and systems:

"*It's quite difficult because it's purely memorising.*" (Participant B)

"*I definitely think spatial awareness and being able to conceptualise the images and work it out in your head.*" (Participant C)

"*I think spatial ability is a more sensitive one, especially when it comes to vascular matters.*"

Theme 3: 3D visualisation

Participating students believed they required more resources to improve their 3D visualisation and their anatomy learning, especially during revision. Participants also reported that the Sectra VT and 3DP models supported their understanding of cross-sectional images:

"I really enjoy it when we go and do the body and then use the Sectra to go up through the body." (Participant A)

"*I think recently especially since the SSC [student selected component project] students are allowed to use Sectra more often.*" (Participant D)

"*I think the 3DP idea is really good since you can take it away to let you handle it, having something physical that you can see and move around.*" (Participant D)

"*I guess with the 3DP, it's like we are going to be able to have prosection outside the DR (dissection room).*" (Participant C)

"*I think the 3DP is really the key thing.*" (Participant D)

"It would be nice if in the future you could use your own printing credit to be able to print all kinds of 3DP models." (Participant B)

"*One thing I really like is using the Virtual Human dissector. I know it's a very expensive program, but it would be nice if it was available.*" (Participant C)

6.1.9 PA student questionnaire completion rate and demographic (academic year 2018/2019)

The 2018/2019 PA Programme at Newcastle University (**Table 5.3**) was selected for a pilot study to validate questionnaire items (**Table 5.7**) and to evaluate the Sectra and 3DP resources. The first part of the questionnaire focused on challenging topics that the PA students faced when studying anatomy. In the study, 17 out of 19 PA students (89%) participated in the questionnaire, including 2 males (12%) and 15 females (88%). The internal consistency of the questionnaire items was verified by Cronbach alpha with a value of 0.89, which is within the acceptable range of 0.70–0.90.

6.1.10 PA students' perceptions and insights about challenging topics in anatomy

The perceptions of participating PA students (n = 17) regarding challenging areas of anatomy learning were investigated based on their responses to questionnaire items in the form of a seven-point Likert-type scale. In each case, items achieving a mean value > 4 and a response rate > 50% were considered to be challenging for the cohort overall. Statistical significance was analysed by Friedman's test, where $P < 0.05$ was considered to be statistically significant and $P < 0.001$to be highly significant. PA students perceived that clinical imaging was more challenging than gross anatomy (mean = 4.41, SD ± 1.33) and significantly ($P < 0.05$) more challenging when compared with surface anatomy (**Figure 6.12**). The second item covered the difficulty of understanding particular anatomical regions. **Figure 6.13** shows that the students found only the limbs to be challenging (mean = 4.88, SD ± 1.45), while they did not find the abdomen (mean = 3.35, SD ± 1.58) or thorax (mean = 3.29, SD ± 1.40) to be challenging.

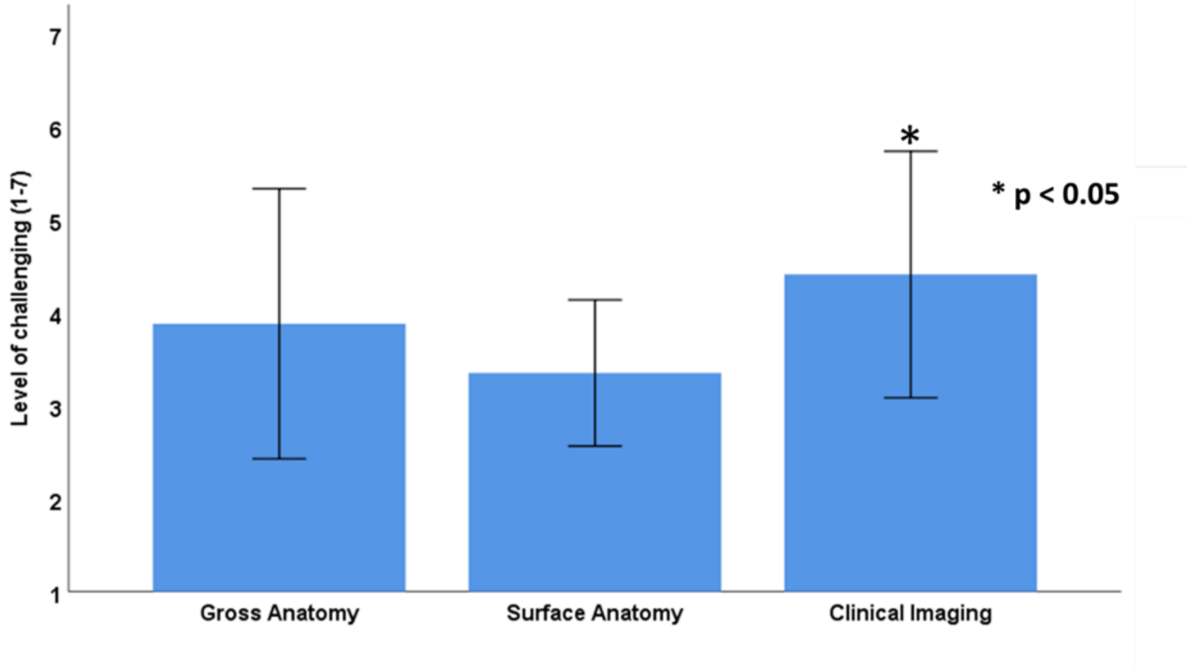


Figure 6.12. PA students' perceptions and insights about challenging topics in anatomy. A mean score > 4 indicates that a topic is challenging overall, where 1 = not challenging at all, 2 = not challenging, 3 = less challenging, 4 = neutral, 5 = slightly challenging, 6 = challenging, and 7 = extremely challenging. Clinical imaging was considered to be the most challenging topic. Clinical imaging was perceived as significantly more challenging (*P < 0.05) when compared with surface anatomy. With mean values < 4, gross anatomy and surface anatomy were not challenging topics for the PA students (n = 17).

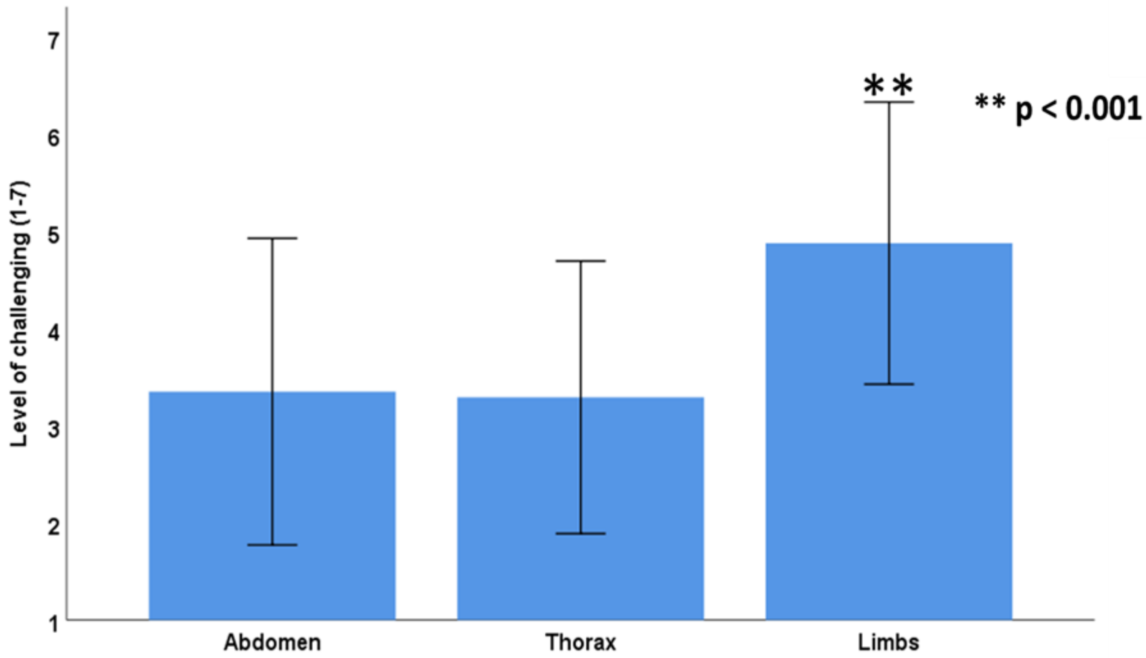


Figure 6.13. PA students' perceptions and insights of challenging regions in anatomy. Out of the three regions covered by the PA students (n = 17) when they studied anatomy, only the limbs were considered to be challenging, while the abdomen and thorax were not challenging. A highly significant difference in complexity level was determined by Friedman's test between regions. The limbs showed a highly significant difference in difficulty level (**P < 0.001) compared with the abdomen and thorax.

When the PA students were asked about the difficulty of understanding certain visceral organs, they did not report that any of the organs they had studied were difficult to understand (**Figure 6.14**). The overall response to the fourth item was expected, where most of the students found that the nerves and plexuses (mean = 4.82, SD ± 1.38) plus the muscles and tendons (mean = 4.65, SD ± 1.50) were difficult to understand (**Figure 6.15**). The nerves and plexuses and the muscles and tendons were considered to be significantly ($P < 0.05$) more challenging to understand than the organs as structures.

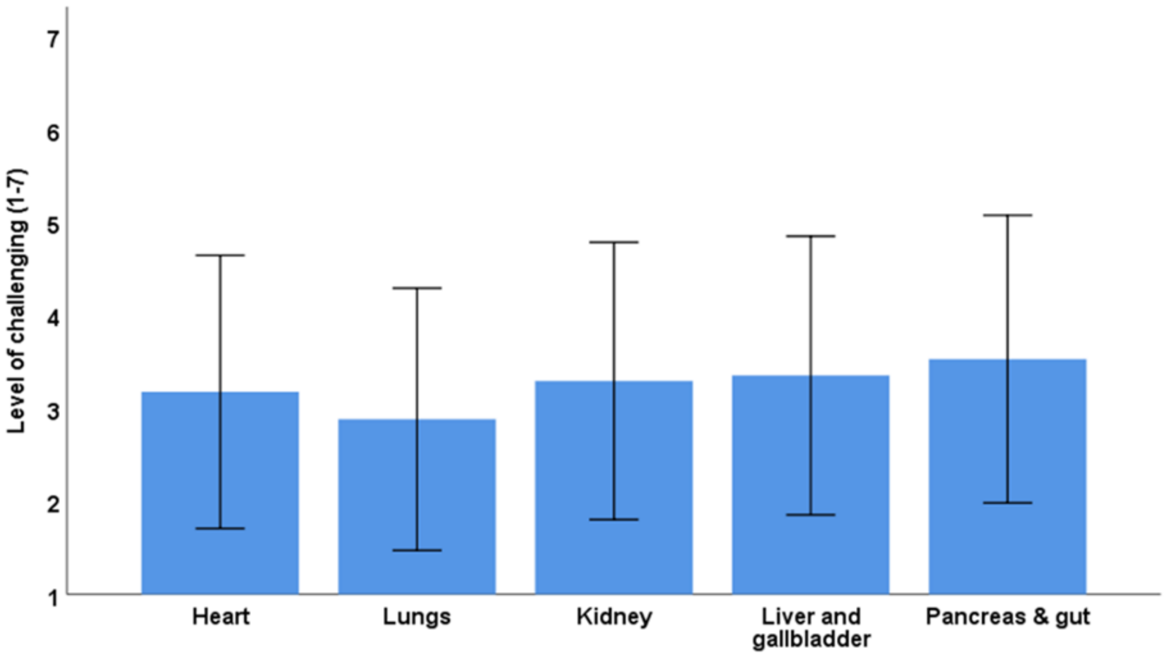


Figure 6.14. PA students' perceptions and insights for challenging anatomical organs. A mean score > 4 indicates that a topic was challenging, where 1 = not challenging at all, 2 = not challenging, 3 = less challenging, 4 = neutral, 5 = slightly challenging, 6 = challenging, and 7 = extremely challenging. Student responses to Likert-type scale items had mean values < 4 for all organs, indicating that the students did not find those organs hard to understand.

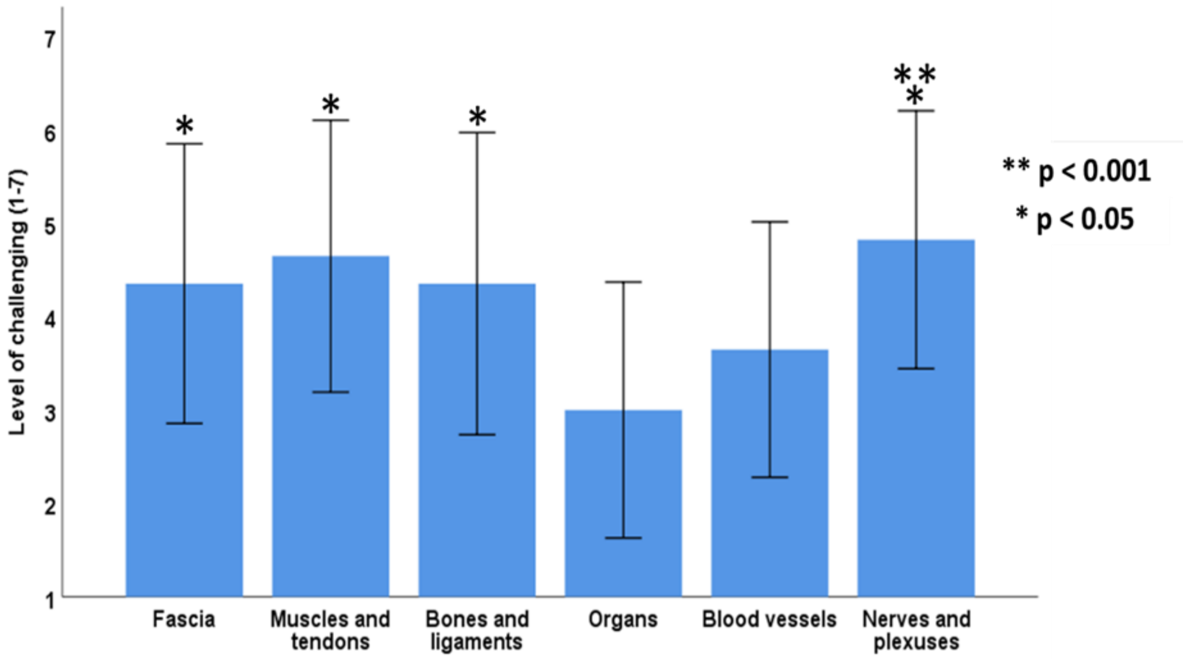


Figure 6.15. PA students' perceptions and insights for challenging structures in anatomy. The nerves and plexuses and the muscles and tendons were considered by the students (n = 17) to be the most challenging structures. The perceived difficulty level of the nerves and plexuses indicated a highly significant difference (**P < 0.001) from that of the organs and a significant difference from that of the blood vessels (*P < 0.05). The muscles and tendons, fascia, and bones and ligaments were all considered to be significantly more challenging than the organs (*P < 0.05).

6.1.11 Anatomy and cross-sectional images

PA training includes interpreting anatomical structures in cross-sectional clinical images from CT and MRI scans to obtain a better understanding and knowledge of the human body and its constituent structures (Al Qahtani and Abdelaziz, 2014). The first questionnaire item showed that clinical imaging is considered the most difficult area in anatomy in terms of the PA students' perceptions. This questionnaire item further investigated the students' perceptions to find more details about the most challenging area for students in interpreting clinical images. Those who responded to this item felt that only muscle compartments (mean = 4.53, SD ± 1.62) were challenging to interpret on cross-sectional images (**Figure 6.16**). PA students perceived that muscle compartments were significantly ($P < 0.05$) more challenging to interpret in clinical images than the heart, liver, and abdomen.

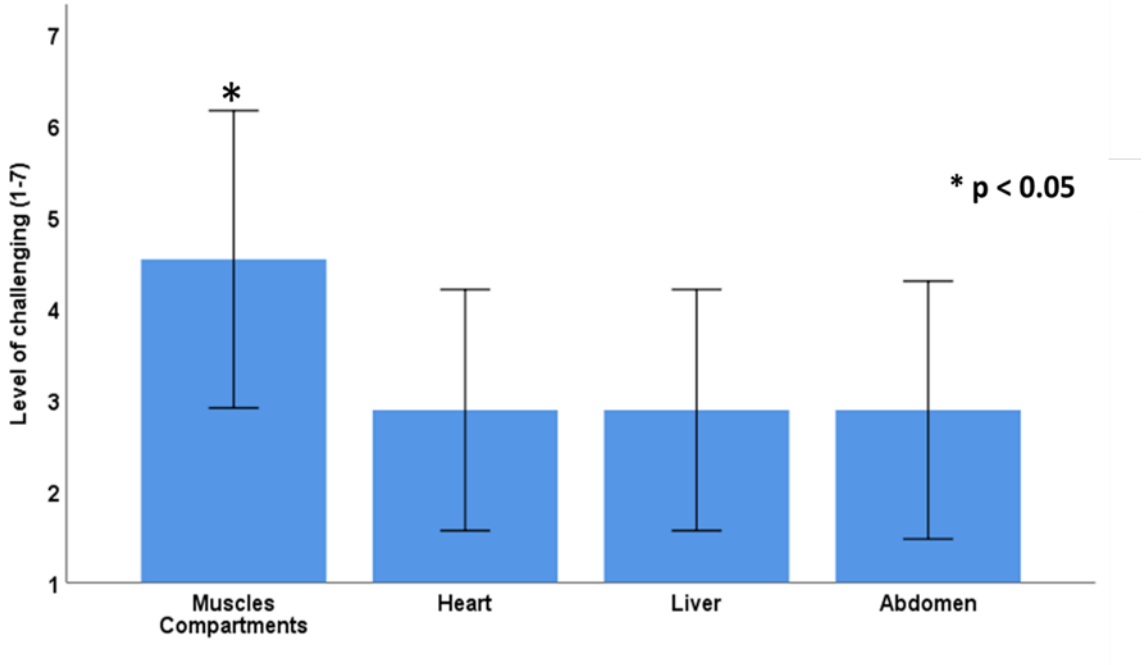


Figure 6.16. Anatomy and cross-sectional images.
The muscle compartments were considered to be the only challenging structures to identify in cross-sectional images (mean = 4.53, SD ± 1.62). Friedman's test showed that muscle compartments were perceived as significantly more challenging to interpret (*P < 0.05) by PA students (n = 17) than the heart, liver, and abdomen.

6.1.12 Factors that make anatomy a challenging course for PA students

The volume of content to learn (mean = 5.29, SD ± 1.72) was the top factor reported by the PA students as making anatomy a difficult course (**Figure 6.17**). The second factor was anatomical terminology (mean = 4.59, SD ± 1.91) **(Figure 6.17)**. The participant responses regarding other factors (teaching contact time, lack of resources, 3D spatial relationships, and understanding 3D anatomical features) resulted in mean values below 4 (**Figure 6.17**), indicating an overall disagreement of whether these factors are related to the challenging concepts of anatomy.

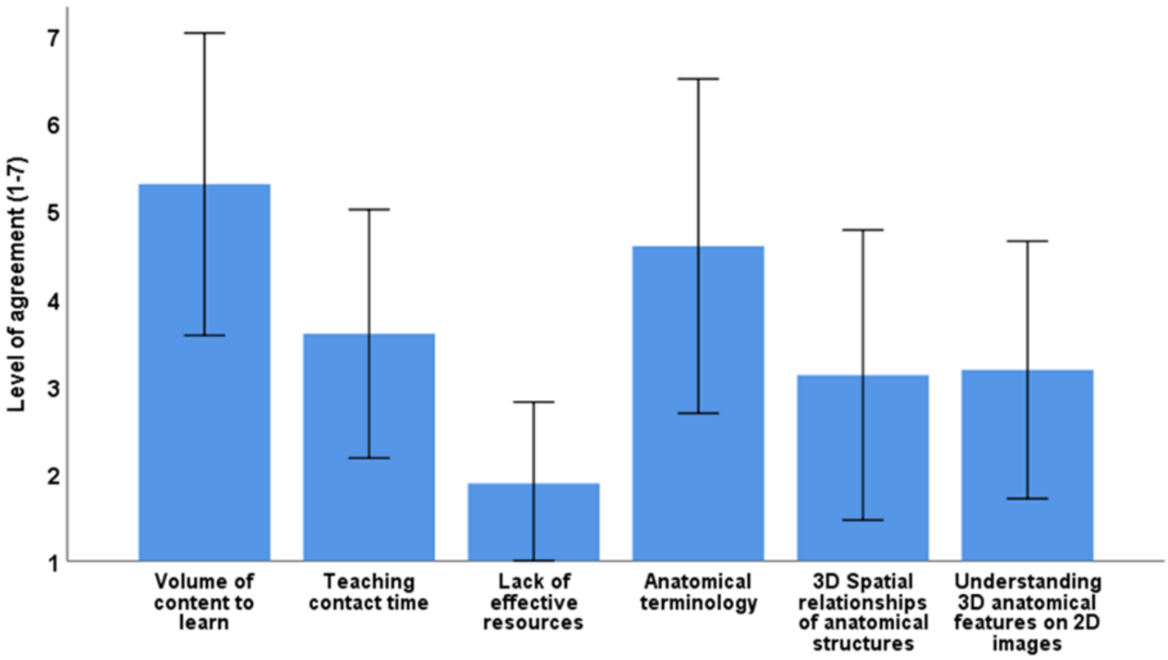


Figure 6.17. Factors behind the challenging concepts of anatomy.
A mean score > 4 indicates overall agreement, where 1 = strongly disagree, 7 = strongly agree. Students show an overall agreement (mean score > 4) that the volume of content to learn and anatomical terminology are the main reasons behind the challenging concepts of anatomy. Other factors, including teaching contact time (mean = 3.58, SD ± 1.42), lack of effective resources (mean = 1.88, SD ± 0.93), 3D spatial relationships (mean = 3.12, SD ± 1.65), and understanding 3D anatomical structures in 2D images (mean = 3.18, SD ± 1.47), were not factors influencing the challenging concepts of anatomy.

6.1.13 Skills needed to improve performance in anatomy learning

The response rate of 89% (n = 17) for this item indicates that the participants perceived certain skills and abilities as important when learning anatomy (**Figure 6.18**). Based on the mean values of the PA students' responses, participants showed an overall agreement that the following skills were needed to enhance their learning of human anatomy: spatial ability, visual observation, haptic observation (touch), knowledge retention, and connecting different anatomical structures (**Figure 6.18**).

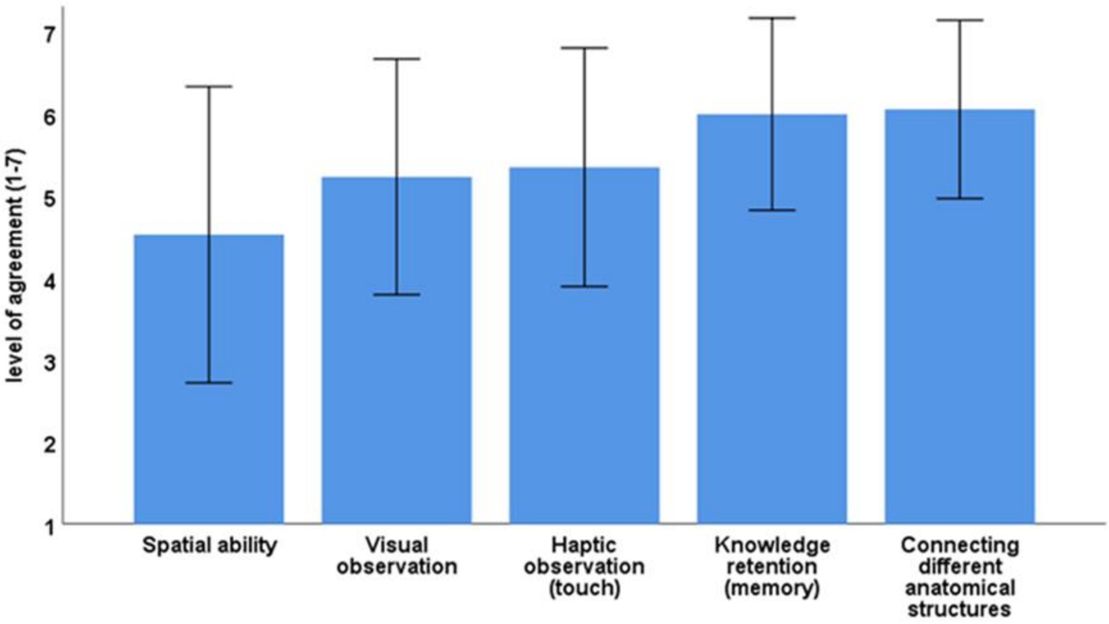


Figure 6.18. Skills needed to enhance anatomy learning.
Student responses to the Likert-type scale showed an overall agreement that all of the mentioned skills were needed to enhance their learning of anatomy (mean score > 4 indicates overall agreement).

6.1.14 Questionnaire completion rate and demographic for the first-year medical students (MBBS)

First-year medical students at the MSNU participated in this study during the first term of the 2018/2019 academic year (**Table 5.3**). Questionnaire items (**Table 5.7, 5.8, 5.9**) were designed to identify the extent of student perceptions with respect to challenging areas and topics in anatomy learning and the use of newly integrated digital and 3D approaches. A total of 319 students (96% of the cohort, n = 330) participated in the questionnaire, including 140 males (44%) and 179 females (56%). Internal consistency for the questionnaire items was verified by a Cronbach alpha score of 0.82 (acceptable range: 0.70–0.90) (Tavakol and Dennick, 2011).

6.1.15 Perceptions of first-year MBBS students regarding challenging topics, regions, and organs in anatomy

In response to the first questionnaire item, 263 of 319 participants (82%) reported that clinical imaging was the most challenging topic when learning anatomy (**Figure 6.19**). Based on mean responses to questionnaire items in the form of a seven-point Likert-type scale (**Figure 6.19**), 221 (69%) out of 319 responders perceived that gross anatomy (mean = 4.92, SD ± 1.22, 69% response rate) was also a challenging topic, where a mean > 4 was considered to indicate an overall challenging by the cohort. Friedman's test revealed a highly significant difference for clinical imaging (P < 0.001) compared with gross anatomy and surface anatomy. At a high level of significance, gross anatomy was more challenging (P < 0.001) when compared to surface anatomy (**Figure 6.19**). **Figure 6.20** shows that students found both the abdomen (mean = 5.61, SD ± 1.10) and thorax (mean = 4.21, SD ± 1.21) to be challenging regions. A Wilcoxon signed-ranks test indicated a highly significant difference (P < 0.001) in difficulty level between the two regions, with the abdomen being more challenging than the thorax (**Figure 6.20**).

Participating students were asked to indicate the extent to which the following structures (heart, kidney, peritoneum) were challenging with regards to anatomical size, shape, and position (**Figure 6.21**). Students found that the peritoneum (mean = 5.83, SD ± 1.03, 89%) was the most challenging, followed by the kidney (mean = 4.20, SD ± 1.31, 41%) (**Figure 6.21**). In this item, most students did not report the anatomy of the heart (mean = 3.48, SD ± 1.28) as challenging.

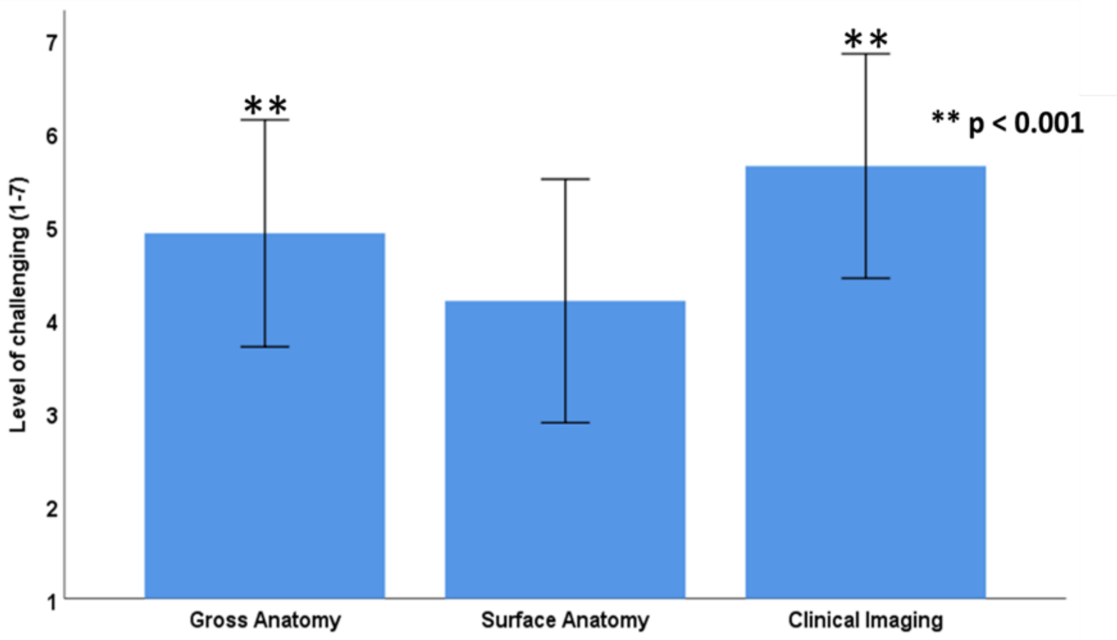


Figure 6.19. Students' perceptions regarding challenging anatomical topics.
A mean score > 4 indicates that a topic is challenging overall, where 1 = not challenging at all, 7 = extremely challenging. Clinical imaging was considered to be the most challenging topic (mean = 5.64, SD ± 1.20). The difficulty level of clinical imaging showed a highly significant difference (**P < 0.001) from that of gross anatomy and surface anatomy. Pairwise comparison showed that gross anatomy was significantly more challenging when compared with surface anatomy (**P < 0.001). The mean values show that all topics were challenging for the students.

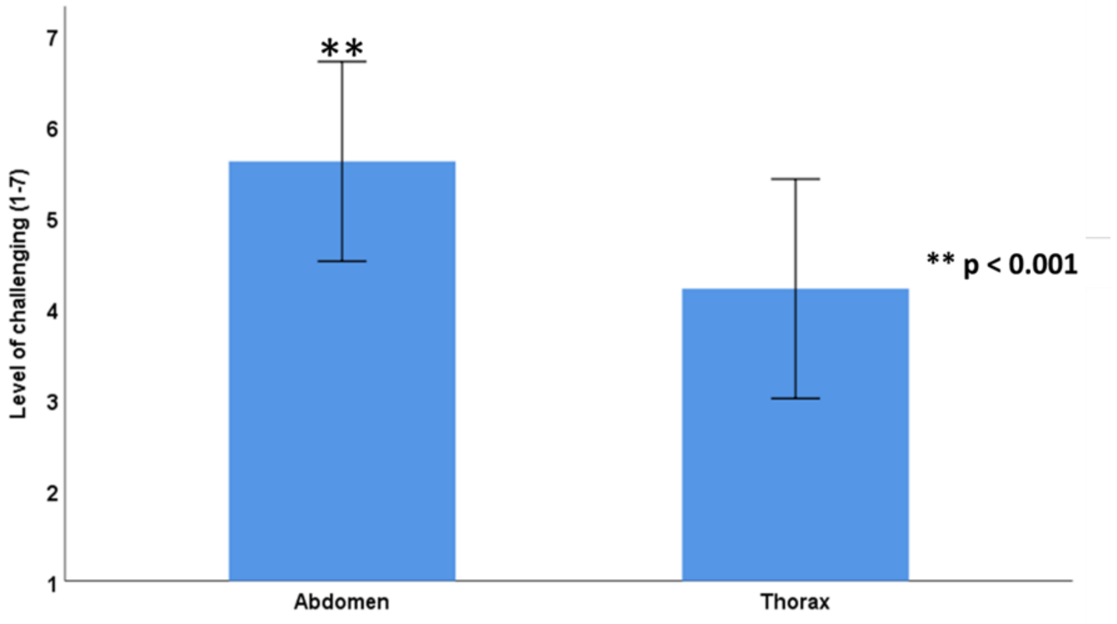


Figure 6.20. Students' perceptions regarding challenging anatomical regions.
Student responses to this Likert-type item (n = 319) showed that both the abdomen and thorax were challenging regions, with means > 4. Wilcoxon signed-ranks tests showed that the abdomen is more challenging than the thorax, with a high level of significance (**P < 0.001).

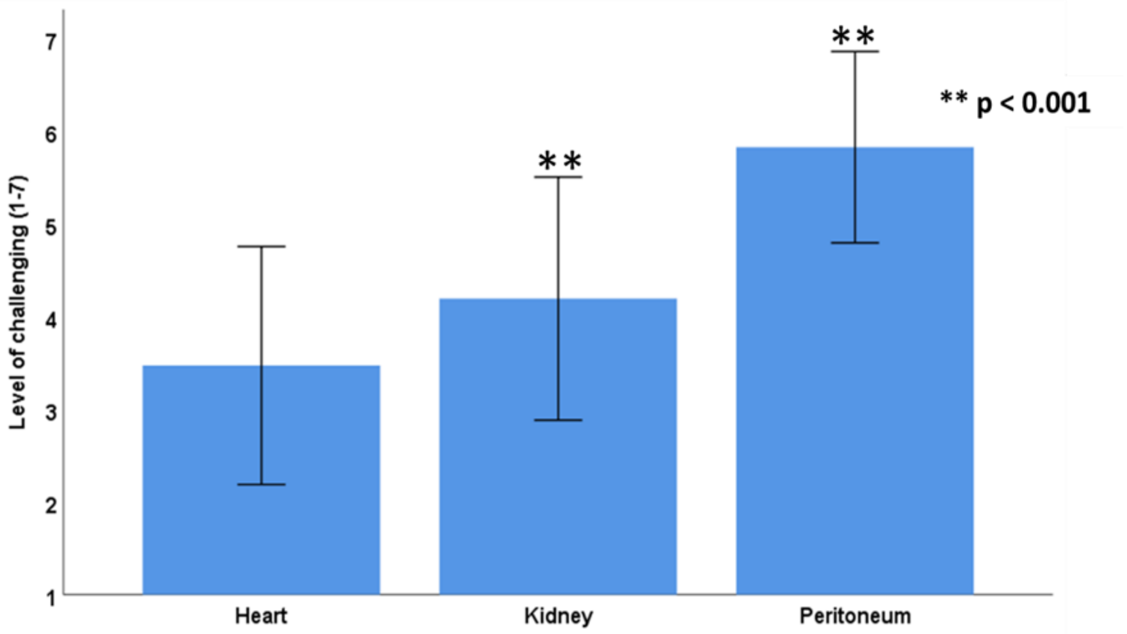


Figure 6.21. Students' perceptions regarding challenging anatomical features.
The peritoneum and kidney were considered to be the only two challenging anatomical features faced by the students when learning anatomy. The heart (mean = 3.48, SD ± 1.28) was not challenging, as its mean value was less than 4. Friedman's test showed a highly significant difference in difficulty level between the three anatomical topics (**P < 0.001). Pairwise comparison showed that the peritoneum and kidney were more challenging than the heart, with a high level of significance (**P < 0.001).

6.1.16 The most challenging areas of anatomy learning

In this section of the questionnaire, the participated students were asked to express their level of agreement regarding particular statements (where a mean > 4 indicates overall agreement of the cohort). Students perceived that the volume of content to learn (mean = 6.06, SD ± 0.95) was the most challenging aspect of anatomy learning, with 93% of students providing responses of 5 or higher (**Figure 6.22**). Participant responses to other factors (teaching contact time, 3D spatial relationships, anatomical terminology, and interpreting 3D anatomical features in 2D images) gave a mean > 4 (**Figure 6.22**), indicating an overall agreement that these factors contributed to the challenges encountered by students when learning anatomy. A lack of effective resources (mean = 2.88, SD ± 1.56) was the only factor upon which the majority of students disagreed (mean < 4), with only 47 (15%) students reporting a lack of effective resources.

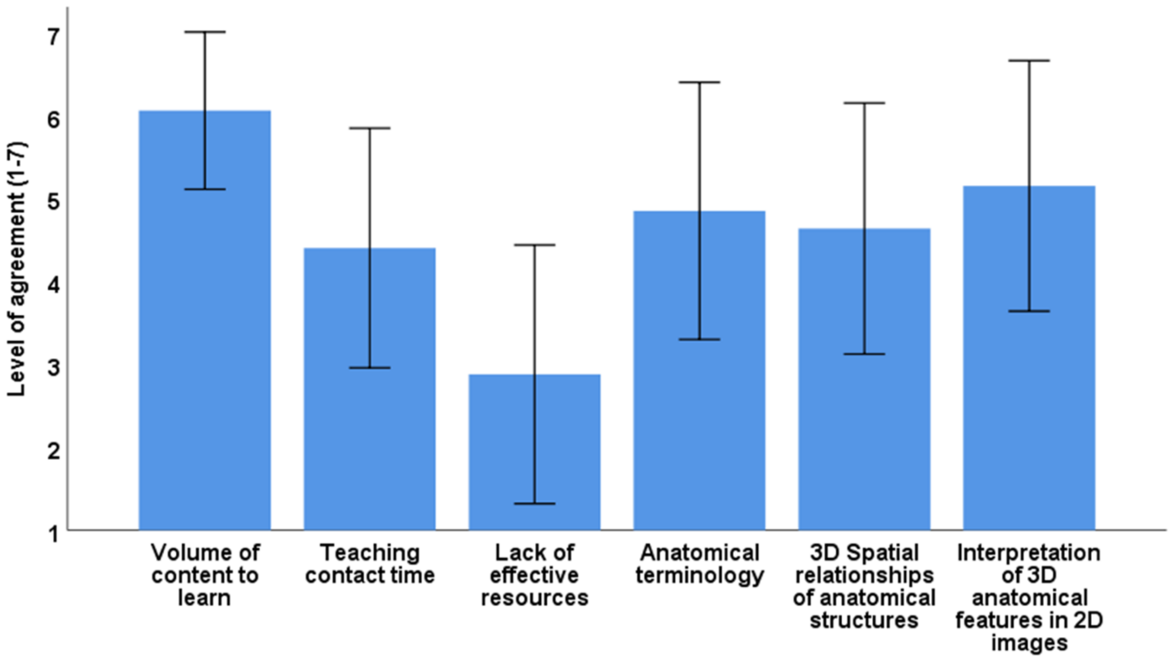


Figure 6.22. Factors behind the challenging concepts of anatomy.
A mean score > 4 with a response rate > 50% indicates that an anatomical feature is challenging for the cohort to understand overall, where 1 = strongly disagree, 7 = strongly agree. A total of 319 student responses to this item showed an overall agreement among student perception that the volume of content was the main reason behind the challenging concepts of anatomy. The other factors, including teaching contact time (mean = 4.40, SD ± 1.45), anatomical terminology (mean = 4.86, SD ± 1.55), 3D spatial relationships (mean = 4.64, SD ± 1.51), and interpretation of 3D anatomical structures in 2D images (mean = 5.15, SD ± 1.50) were also factors behind the challenging concepts of anatomy. A lack of effective resources (mean = 2.88, SD ± 1.56) was the only factor that the students did not report as making anatomy difficult.

A semi-quantitative thematic content analysis (Vaismoradi et al., 2013) was performed to analyse responses to free-text items (n = 87) in the questionnaire, where the students responses were divided into different themes. We calculated the percentage of emerging themes by coding the students' answers. Eight themes arose from the thematic content analysis **(Figure 6.23)**. The responses indicated that participants felt that the volume of content was the most challenging aspect of gross anatomy learning. The remainder of the themes and the proportion of students citing each theme are shown in **Figure 6.23**.

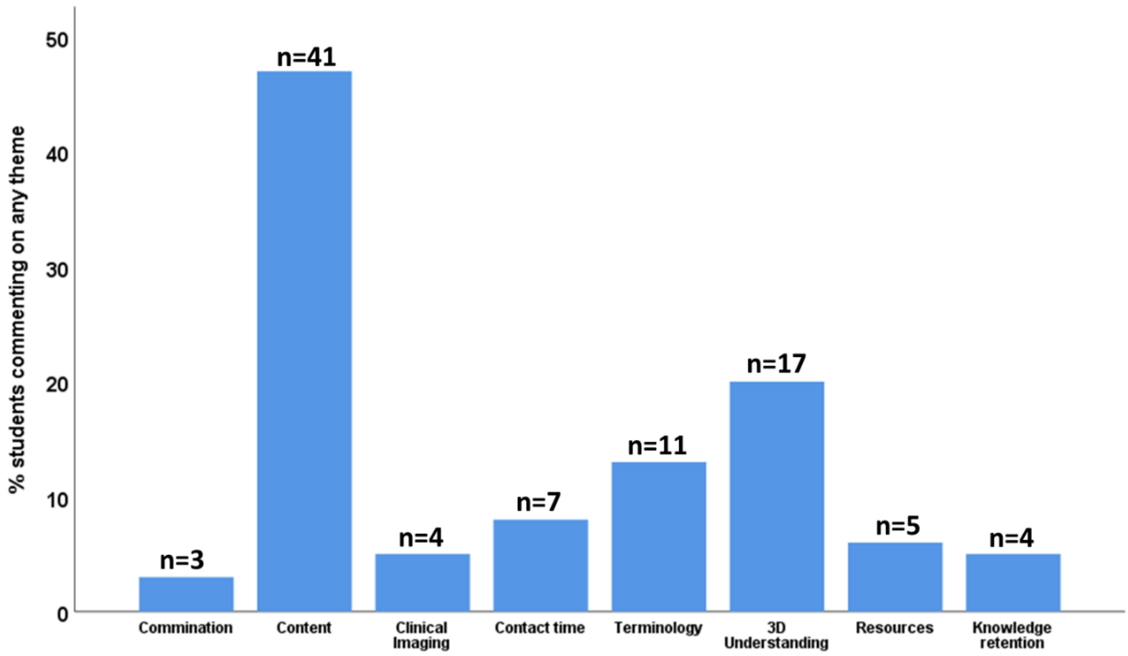


Figure 6.23. Percentage of themes arising from free-text comments regarding challenging areas, topics, or concepts encountered by students in their learning of gross anatomy (n = 87).

6.1.17 MBBS student perceptions of skills needed to improve anatomy learning

The response rate for this item showed that the participants had similar perceptions with respect to the skills needed to learn anatomy (**Figure 6.24**). From the mean values of first-year MBBS student responses, as described above, students agreed that spatial ability, visual observation, haptic observation (touch), knowledge retention (memory), and understanding broader anatomical relationships were needed to enhance their anatomy learning.

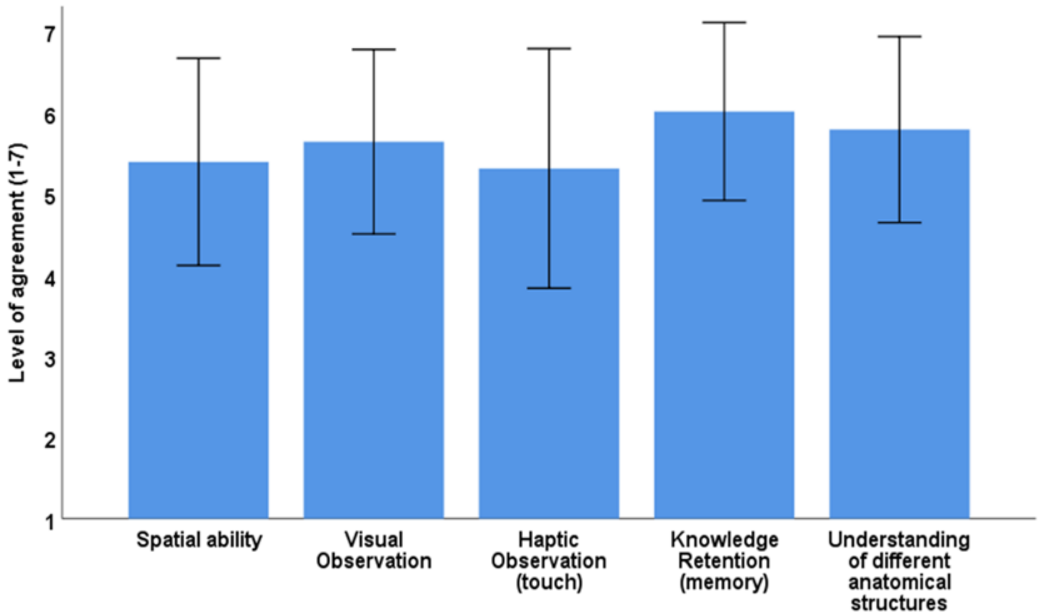


Figure 6.24. Skills needed to enhance anatomy learning.
A mean score > 4 with a response rate > 50% (n = 319) indicated that an anatomical feature was challenging for the cohort to understand overall, where 1 = strongly disagree, 7 = strongly agree. Student responses on the Likert-type scale showed an overall agreement that all of the mentioned skills were needed to enhance anatomy learning.

6.1.18 MBBS students' perceptions of clinical-imaging interpretation

The overall response to this question was expected, as most of the students reported that clinical imaging was the most challenging topic in anatomy (**Figure 6.19**). Analysis of this item showed that both the abdomen and thorax were troublesome for students in terms of their ability to identify and distinguish anatomical features and structures in cross-sectional clinical images (**Figure 6.25**).

Six themes emerged from the semi-quantitative thematic content analysis of a free-text questionnaire item focusing on the anatomical features that students found the most challenging to identify in clinical images (**Figure 6.26**). There was a relatively low cohort response rate to this item (n = 70, 22%). For this item, the majority (51%) of responders perceived that clinical-imaging interpretation in general was challenging, while more specifically, the abdomen and blood vessels were considered to be particularly troublesome.

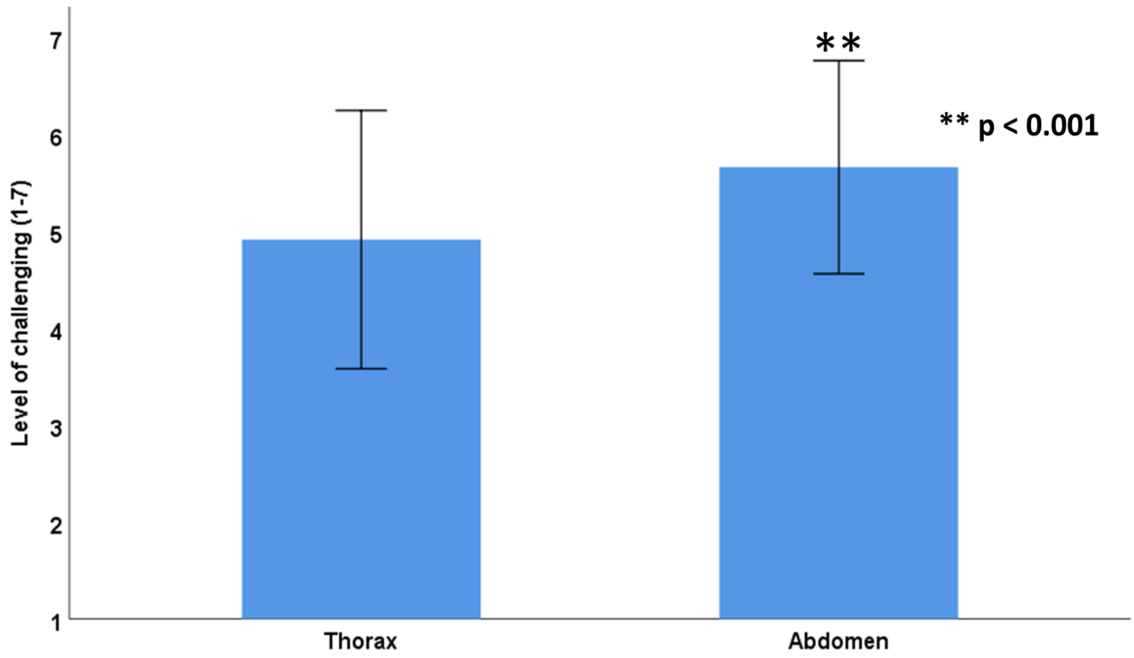


Figure 6.25. Students' perceptions regarding cross-sectional images.
Student responses (n = 319) to this Likert-type item showed that both the abdomen (mean = 5.66, SD ± 1.10, 88%) and the thorax (mean = 4.91, SD ± 1.33, 66%) were difficult to identify in cross-sectional images. A Wilcoxon signed-ranks test showed that the abdomen was more challenging than the thorax, with a high level of significance (**P < 0.001).

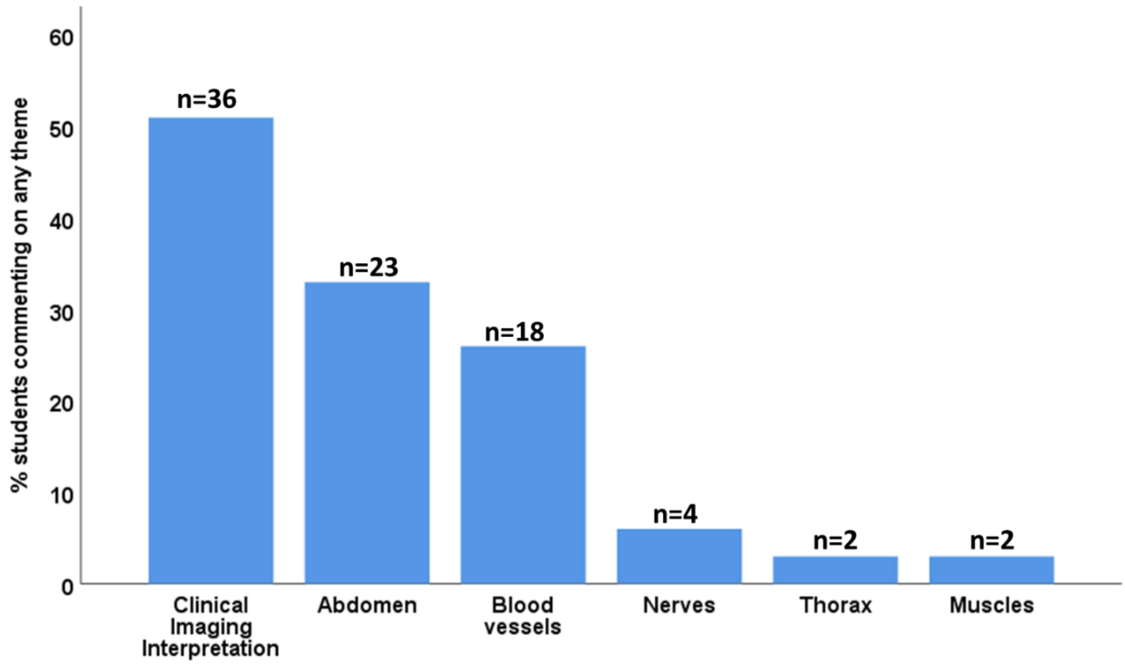


Figure 6.26. Percentage of themes arising from semi-quantitative thematic content analysis

Six themes arose from free-text comments analysis regarding the challenging features reported by students in clinical imaging (n = 70).

6.2 Phase II: Investigating Practical Multimodal 3D Anatomy Learning Resources

Further work was performed to gather more data about the benefits of multimodal 3D anatomy learning resources. In this section, student results from experimental testing, Likert-type questionnaire, and focus group data were analysed.

6.2.1 PA students' perceptions regarding the use of Sectra and 3DP models

Participating PA students (n = 17) were asked to respond regarding their views on any added value they gained from using Sectra and 3DP models. The students were asked to consider how effective these resources would be if they were utilised for self-directed learning. The majority had an overall agreement that these resources added great value for learning anatomy (**Figure 6.27**). To further investigate the usage of Sectra and 3DP models, more detailed items were included (**Figure 6.28, Figure 6.29**). Further analysis showed that the students had positive views of using Sectra and 3DP models as self-directed learning resources to enhance their anatomy learning (**Figure 6.28, Figure 6.29**).

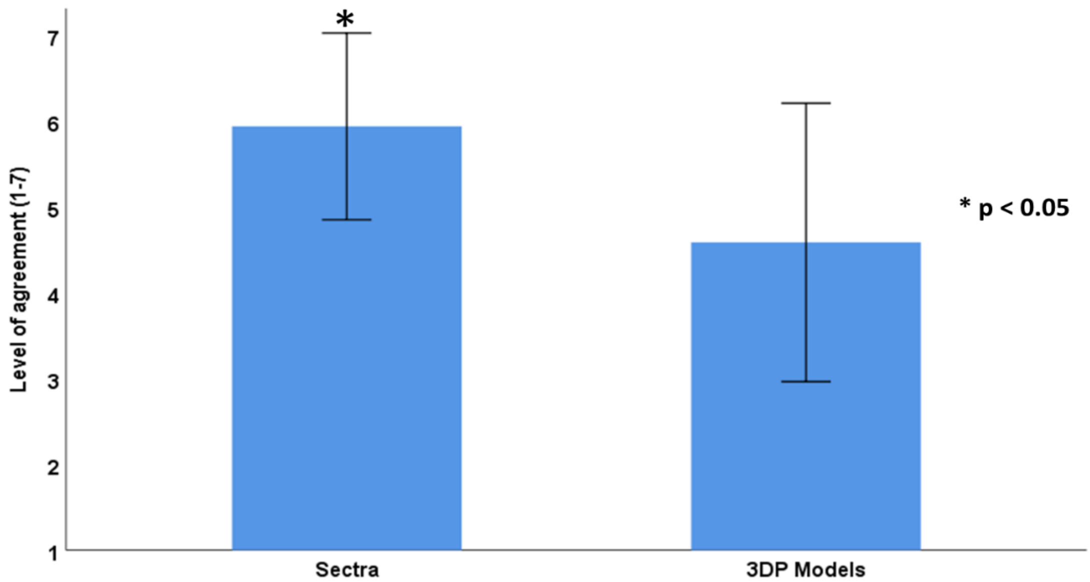


Figure 6.27. Added value of self-directed learning resources.
A mean score > 4 indicates overall agreement, where 1 = strongly disagree, 7 = strongly agree. Student responses (n = 17) showed an overall agreement for the added value of Sectra and 3DP organs as sources of self-directed learning. A Wilcoxon signed-ranks test showed that Sectra (mean = 5.94, SD ± 1.09) was perceived as significantly more valuable (*P < 0.05) than 3DP models (mean = 4.59, SD ± 1.62) as a source of self-directed learning in anatomy.

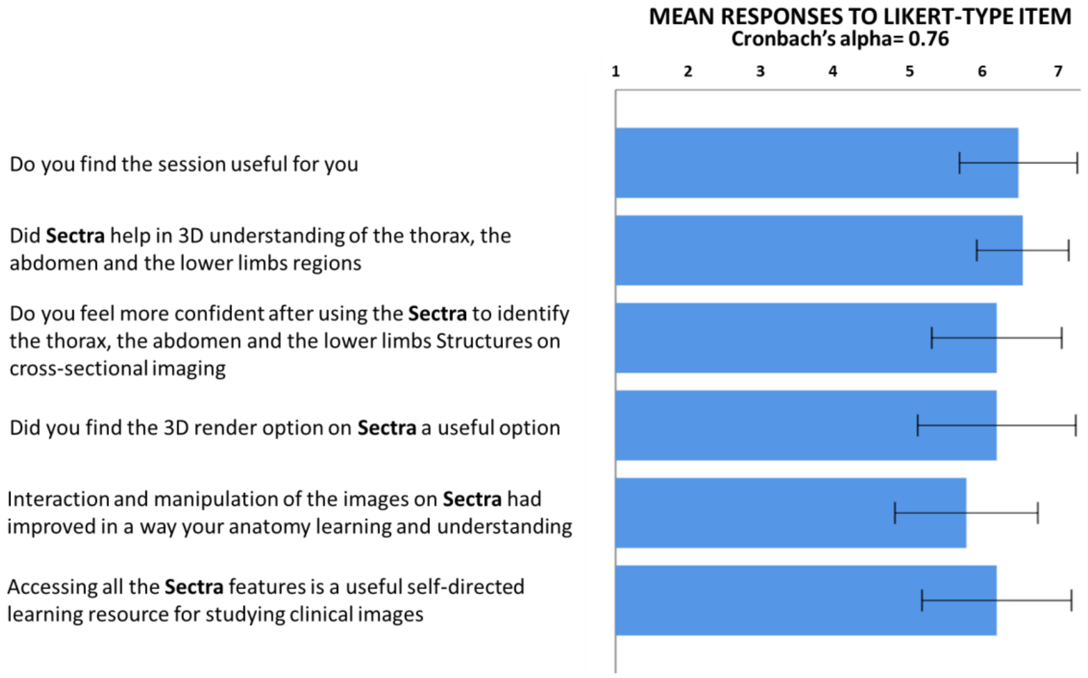


Figure 6.28. Students' perceptions of Sectra usage.

Analysis showed that the means for all items were above 4, indicating overall agreement. The data indicate that responding students (n = 17) found the Sectra practical session to be useful. The students agreed that Sectra improved their 3D understanding of the thorax, abdomen, and limbs. Sectra also increased their confidence in identifying and recognizing structures in cross-sectional images. The '3D render' option was useful for the participants. Interaction with Sectra's features improved the students' understanding of anatomy. Student responses to the last Likert-type item indicate that Sectra, with all of its features, was a useful self-directed learning resource (mean = 6.18, SD ± 1.01).

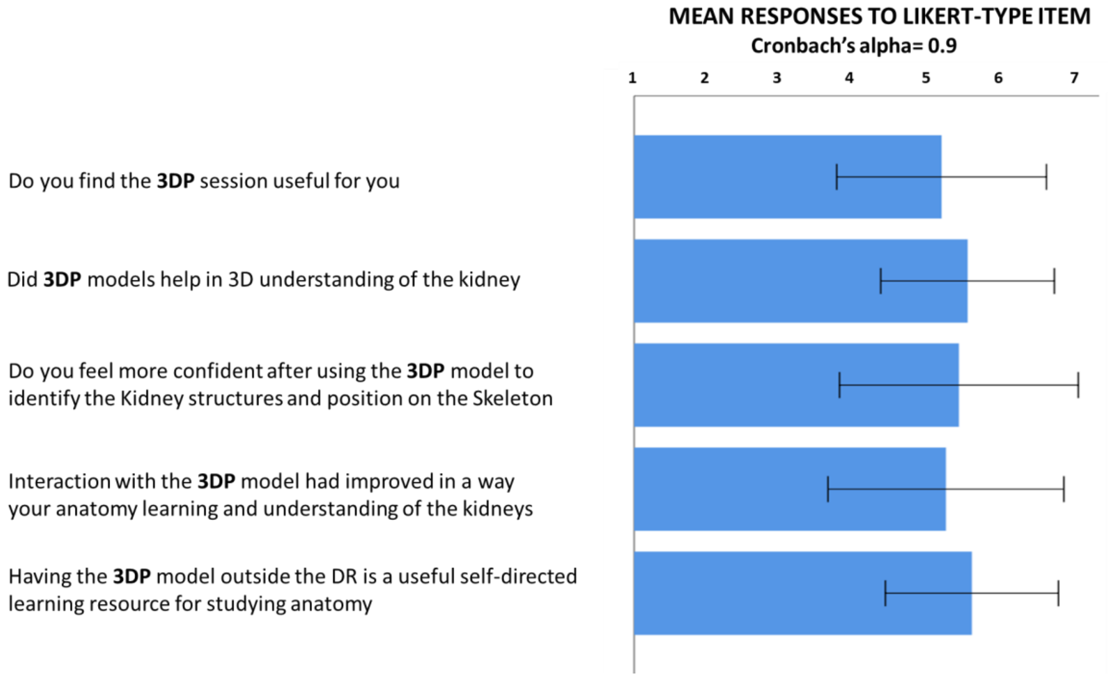


Figure 6.29. Students' perceptions of 3DP model usage.

Data indicate that responding students (n = 17) had overall agreement on all of the items, with mean values above 4. The 3DP model practical session was useful for the students, and they agreed that 3DP models improved their 3D understanding of the kidney. The PA students became more confident in identifying structures of the kidneys. The participants agreed that the 3DP models are a useful self-directed resource to be used outside the DR.

6.2.2 PA students' perception of self-directed resources that enhance anatomy learning

Semi-quantitative thematic content analysis was performed to analyse free-text comments regarding the need for self-directed learning resources to enhance anatomy learning. Themes arising from the analysis indicated that students felt there were many resources that they would need. The key theme in terms of quantity (n = 6, 55%) indicated that most of the students would appreciate more online interactive resources (**Figure 6.30**). The second-most requested resource was 3DP models (n = 3, 27%). The students also recommended the use of anatomy textbooks (n = 1, 9%) and more time in the DR (n = 1, 9%) to enhance their anatomy learning.

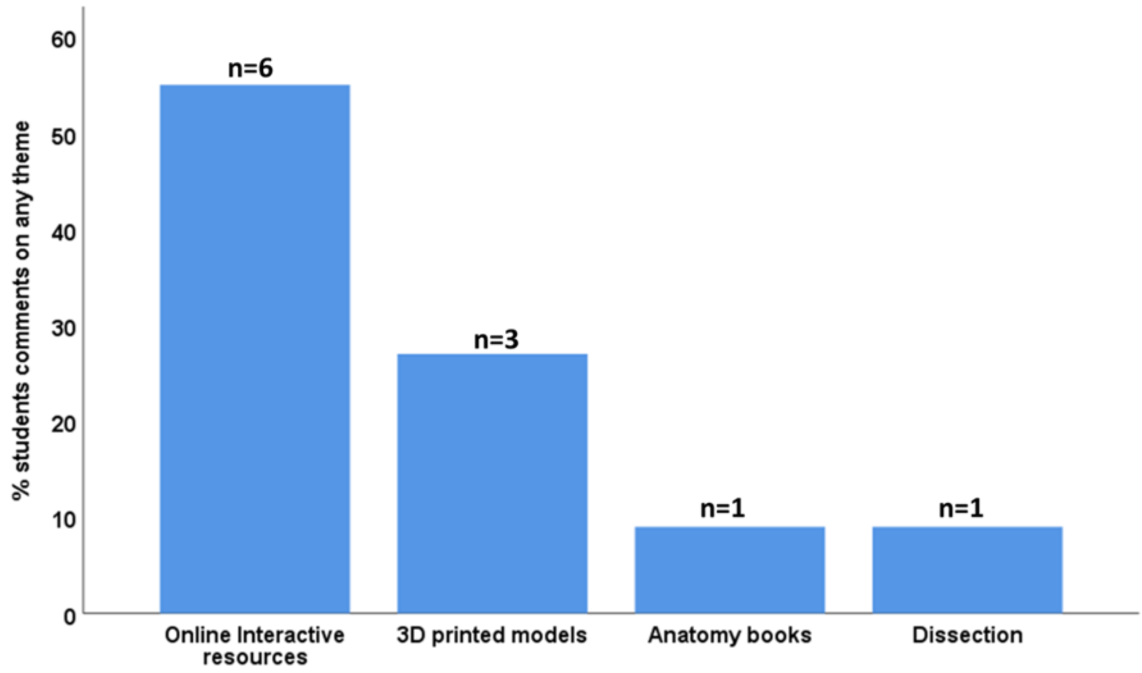


Figure 6.30. Themes arising from free-text comments regarding the need for self-directed resources to enhance anatomy.
Semi-quantitative thematic content analysis was conducted to analyse the students' free-text responses to the following questionnaire item: *Please describe any taught or self-directed resources that would enhance your anatomy learning*.

6.2.3 MBBS students' perception of Sectra usage

The perceptions of first year MBBS students regarding Sectra were identified by responses to Likert-type items (**Figure 6.31**) (Cronbach's alpha = 0.89). In general, the use of Sectra features was valuable for all participants and increased their confidence and ability to identify structures in cross-sectional images. The respondents were asked to suggest other areas in which use of the Sectra could be enhanced. Out of the total cohort (n = 319), 121 (37%) subjects completed a free-text item, and four themes arose from the analysis (**Figure 6.32**).

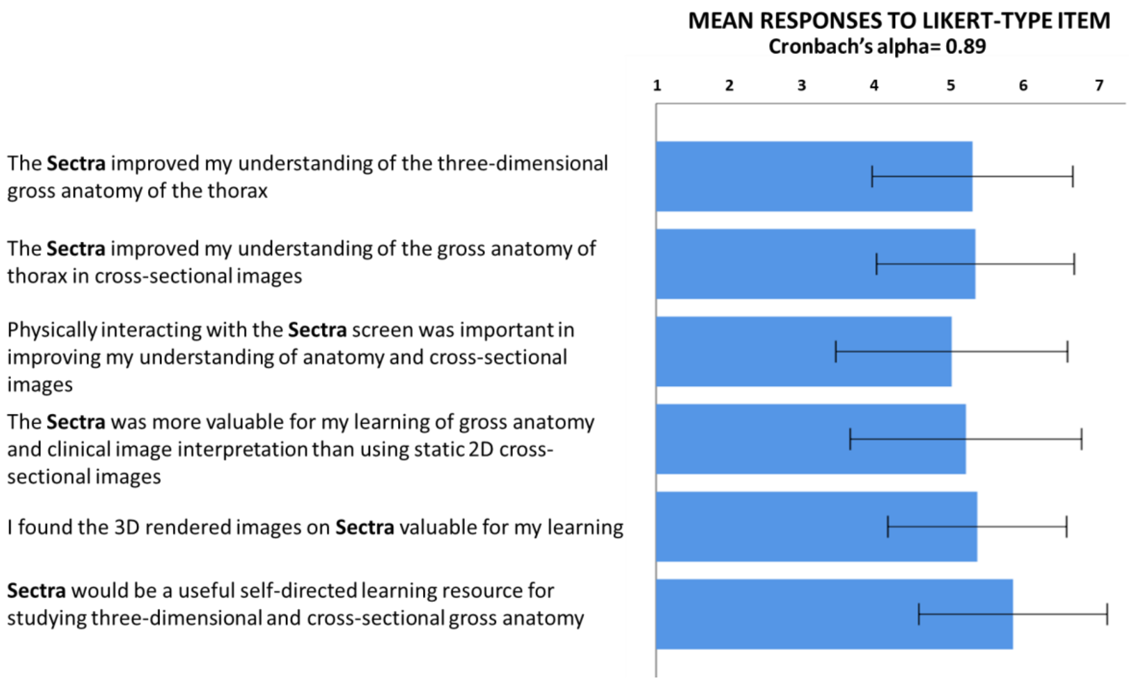


Figure 6.31. Students' perceptions of Sectra usage.

A mean score > 4 indicates overall agreement, where 1 = strongly disagree, 7 = strongly agree. The data indicated that responding students (n = 319) found the Sectra practical session to be useful. The students agreed that Sectra improved their 3D understanding of the thorax and increased their confidence in identifying structures in the heart. The '3D render' option was useful for the participants. Their interaction with Sectra's features improved the students' understanding of anatomy (mean = 5.32, SD ± 1.20).

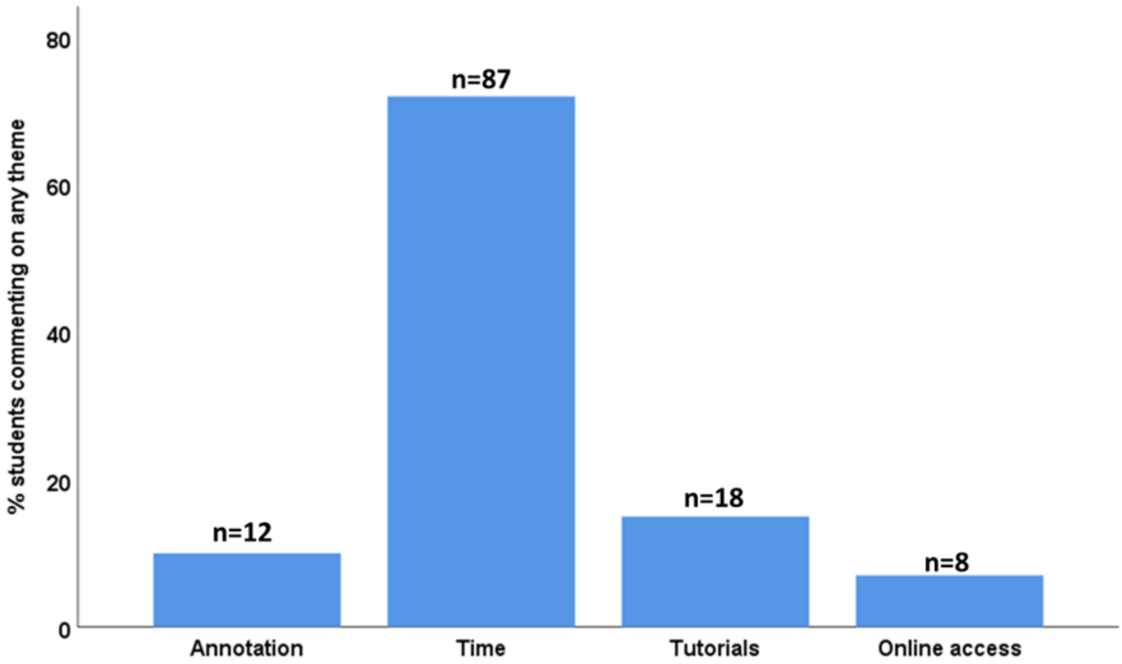


Figure 6.32. Students' perceptions regarding how to improve Sectra usage.
Four themes arose from semi-quantitative thematic content analysis of students' free-text comments (n = 121) regarding how to improve the use of Sectra. Overall, 72% of the students felt that they needed more time to use Sectra and to be more involved in the practical session.

6.2.4 MBBS students' perceptions of 3DP model usage

This section of the questionnaire asked respondents to provide their insights into the usage of 3DP models. A majority of the participants perceived the 3DP models of the heart to be useful for learning anatomy (**Figure 6.33**). A free-text questionnaire item was analysed, and six themes arose from the analysis. The percentage of the participating students mentioning each theme is shown in **Figure 6.34**. Primarily, students felt that the models needed to be more detailed and perceived value in the ability to take 3DP models out of the DR for self-directed learning.

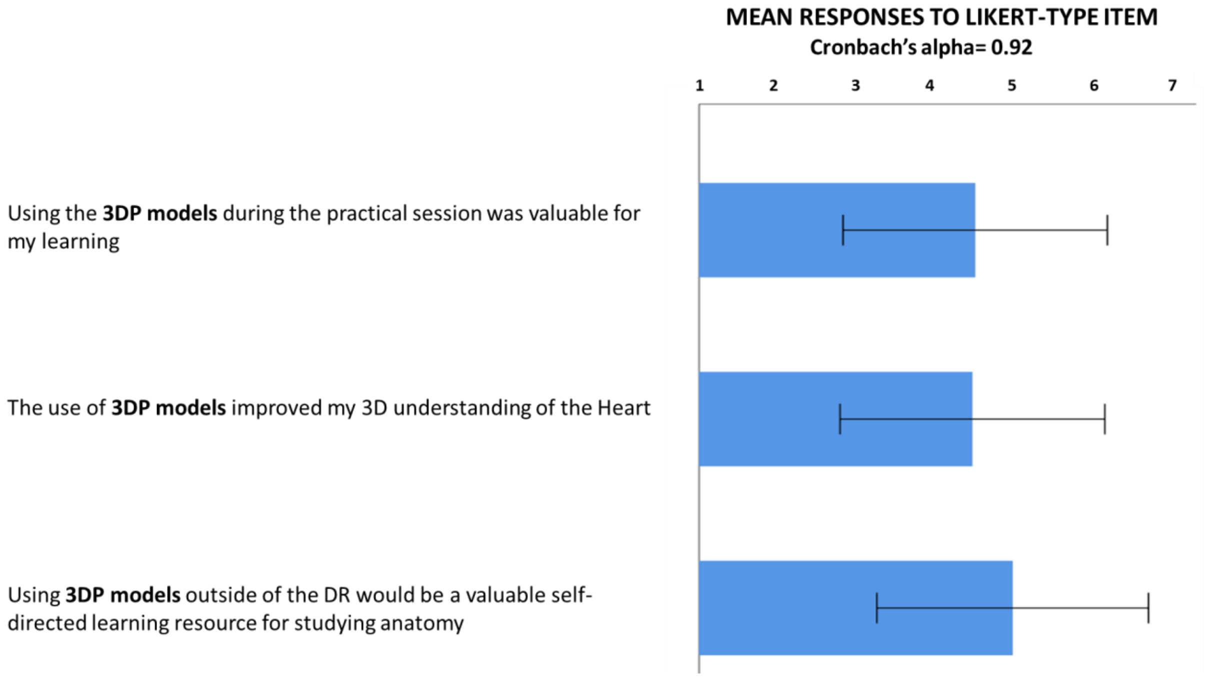


Figure 6.33. Students' perceptions of 3DP models.
Means of student responses to Likert-type questionnaire items regarding 3DP model usage during practical sessions. For all items, the students had an overall agreement that the 3DP models of the heart were useful during anatomy learning (mean > 4).

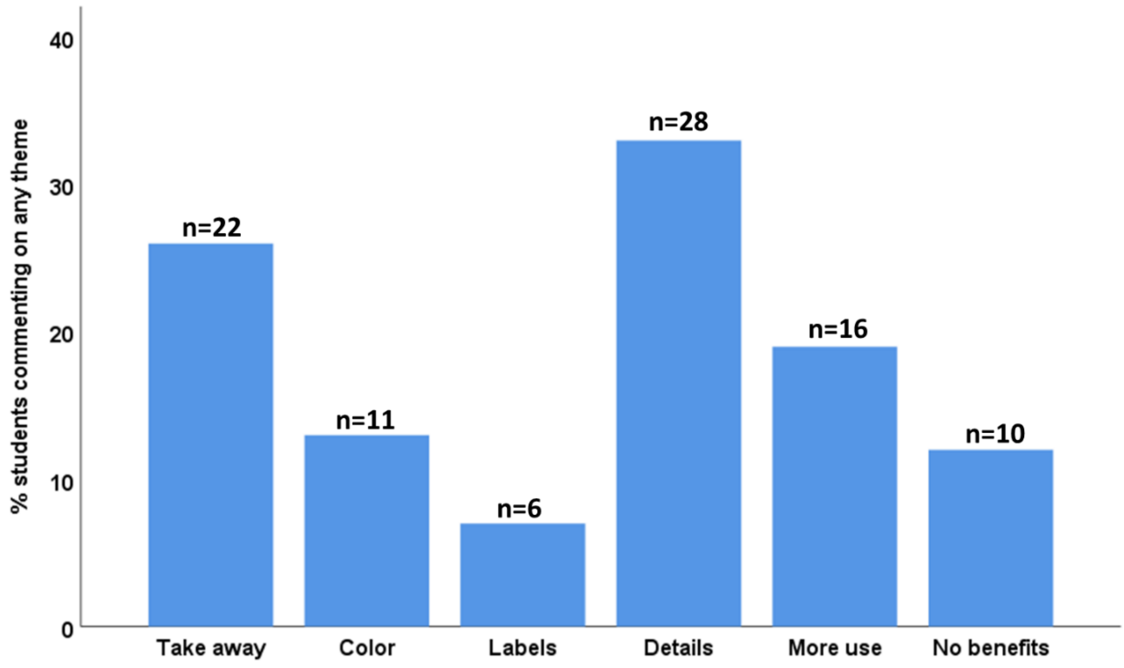


Figure 6.34. Students' perceptions regarding how to improve 3DP usage.
Six themes arose from semi-quantitative thematic content analysis of free-text comments regarding how the use of 3DP models can be improved. The data were collected from 86 individuals, 28 of whom agreed that the models required more detail to improve their use during anatomy learning. Being able to take the 3DP models out of the DR was considered the second theme for aiding anatomy learning.

6.2.5 MBBS students' insights regarding the need for self-directed learning resources

In total, 150 students commented about the need for self-directed resources to enhance and improve their anatomy learning. Based on a semi-quantitative thematic content analysis of free-text answers, students perceived that online interactive resources were the primary self-directed learning approach required when studying anatomy **(Figure 6.35)**.

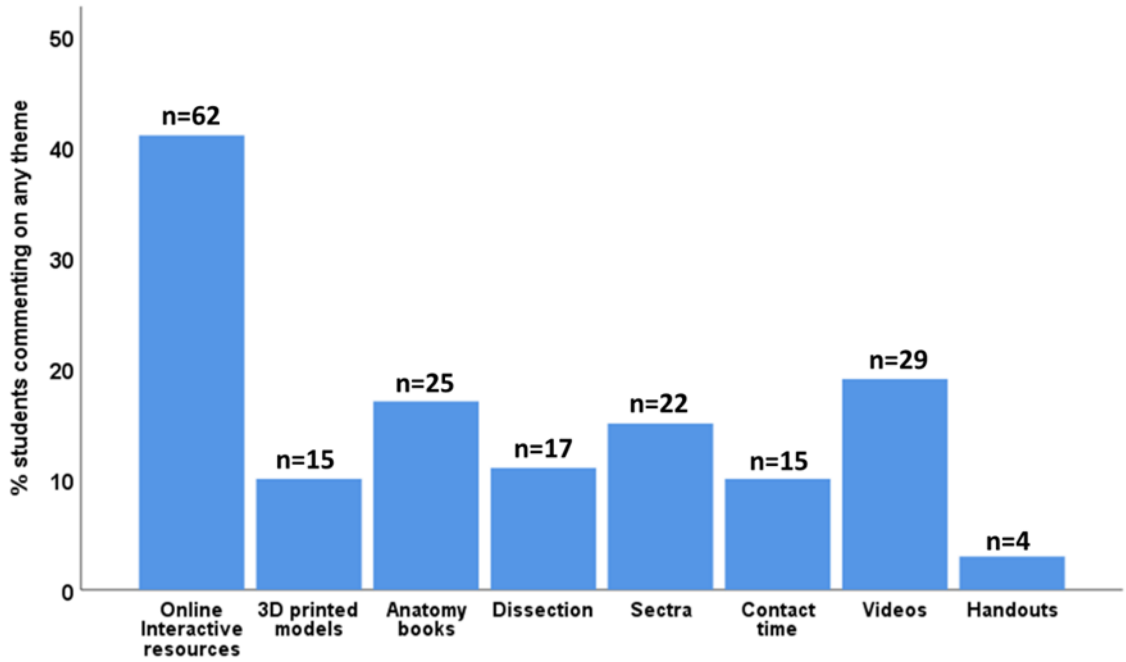


Figure 6.35. Students' perceptions of necessary self-directed resources.
Eight themes arose from a semi-quantitative thematic content analysis of the answers to the free-text item regarding the need for self-directed resources to enhance and improve anatomy learning. The data were collected from 150 individuals, 62 of whom reported a need for more online interactive resources to enhance their anatomy learning. In addition, 29 students commented that videos would be useful as a self-directed learning resource.

6.2.6 Sectra pilot study

A Sectra pilot study was performed to design the actual learning activity, to practice usage of the Sectra, to practice the data analysis, and to practice the logistics and not to collect data. The pilot data is not valid for complete analysis or interpretation as only five students participated. The gathered results from the pilot are shown in **Figures 6.36**, **6.37**, and **6.38**.

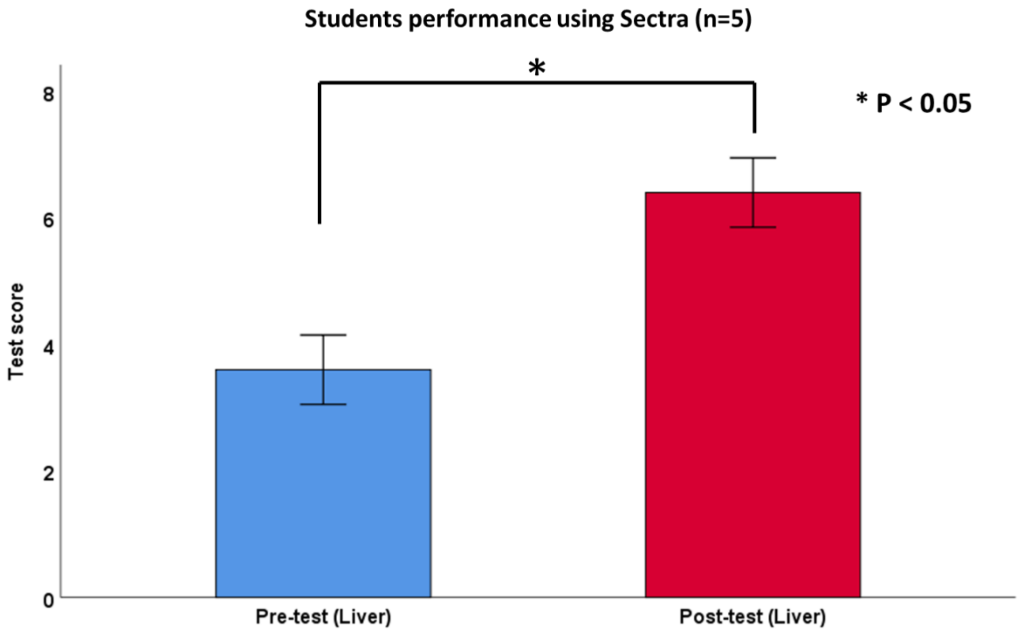


Figure 6.36. Pre- and post-test results in the Sectra pilot study.
The volunteered SSC students' (n = 5) used the Sectra, and a paired t-test showed that their improvement was significant (*$P < 0.05$) based on a comparison of pre- and post-test results.

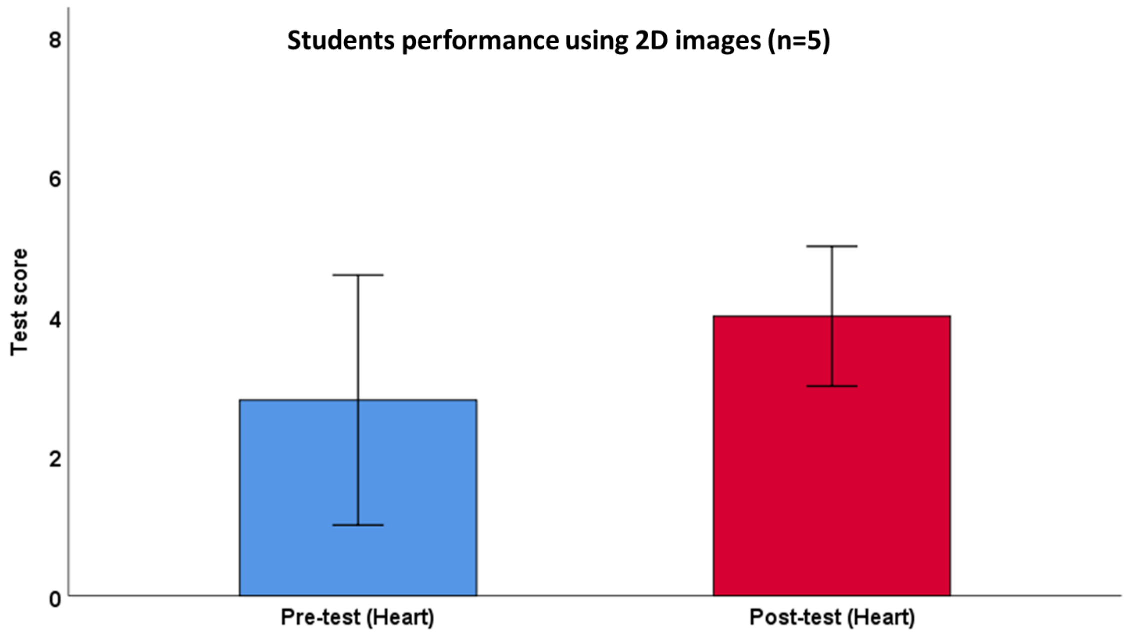


Figure 6.37. Pre- and post-test results of using 2D images in the pilot study.
The same SSC students (n = 5) were tested after using 2D images, and a paired t-test showed that the difference between the pre-test and post-test results was not statistically significant.

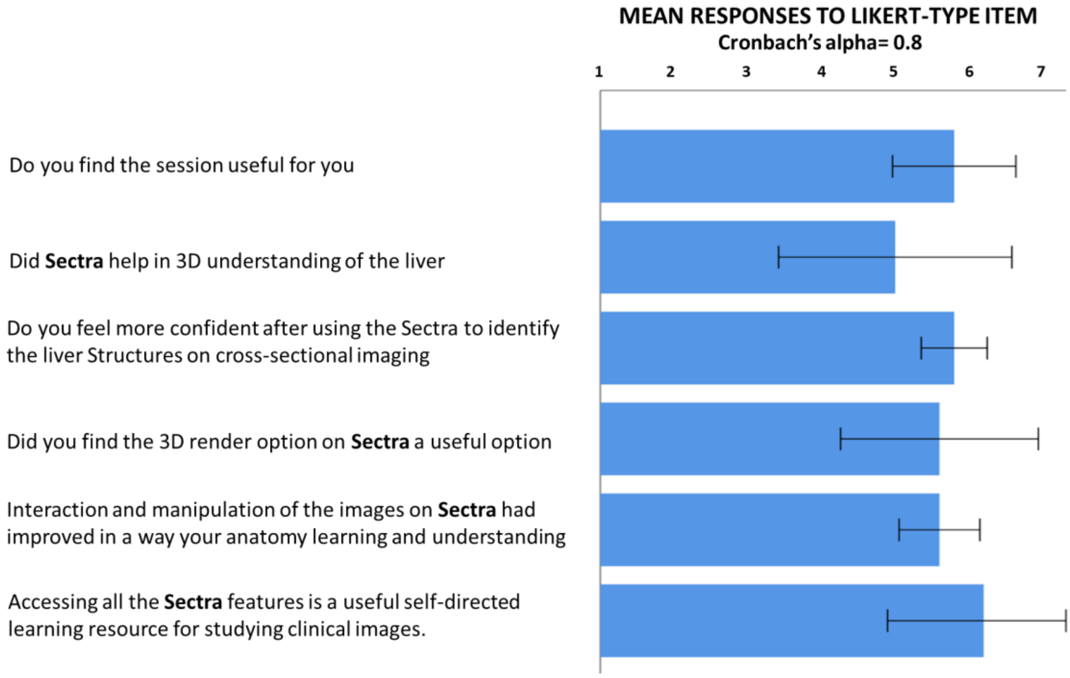


Figure 6.38. Students' perceptions of Sectra usage (pilot study).
The data indicated that responding students (n = 5) found the Sectra practical session to be useful.

6.2.7 MBBS student performance using Sectra, 3DP models, and 2D images

In the 2018/2019 academic year, 229 first-year students (69% response rate, cohort n = 330) participated in the quantitative part of this study. Student abilities and improvements in interpreting cross-sectional clinical images were tested in two anatomy practical teaching sessions. In the thorax sessions, the students used Sectra and 3DP models to interpret clinical images of the thorax. Before the session, the students took part in a pre-test (mean = 2.6, SD ± 1.24) followed by an immediate post-test once the session was complete (mean = 6.4, SD ± 1.87) (**Figure 6.39**). A paired t-test showed that the improvement between the pre- and post-tests was highly significant ($P < 0.001$) (**Figure 6.39**). The pre-test and post-test were administered to students in the abdomen session, where they used only 2D images to interpret clinical images of the abdomen. The pre- and post-test scores showed a highly significant improvement ($P < 0.001$) in student performance **(Figure 6.40)**. To compare the level of performance between the two sessions, student performance was calculated by identifying the difference between the pre-test and post-test scores in both the thorax session (integrated and combined Sectra and 3DP models) and the abdomen session (2D images) (**Figure 6.41**). Statistical analysis showed that the improvement in the student performance when using Sectra and 3DP models was highly significant compared with the use of 2D images only. These results indicate that Sectra and 3DP models are effective resources for improving students' abilities in interpreting clinical images.

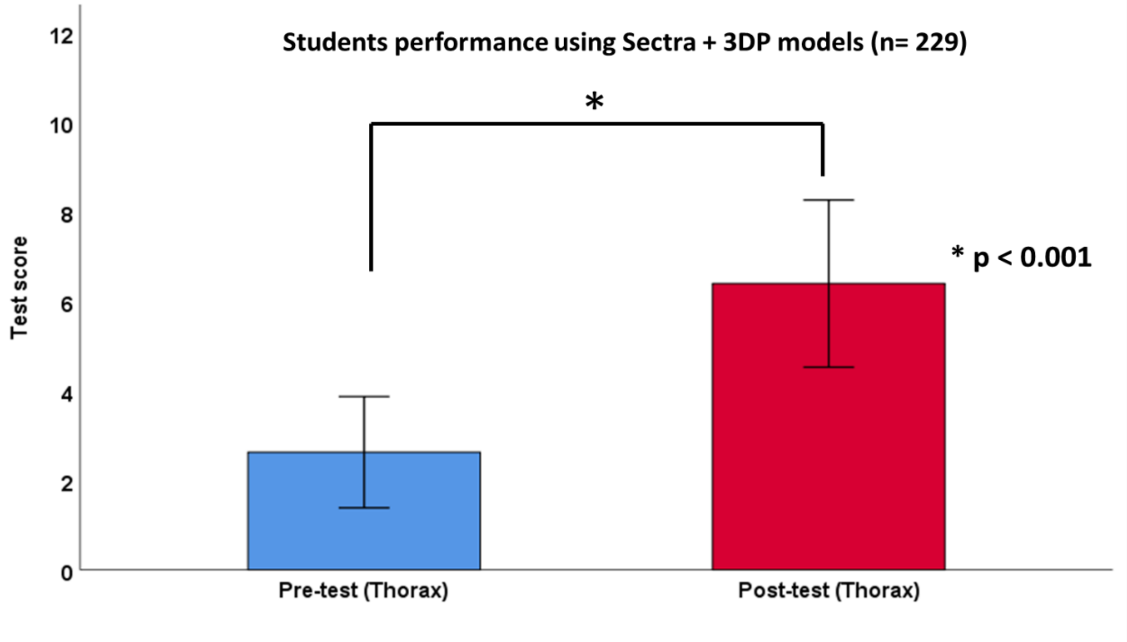


Figure 6.39. Students' performance when using Sectra + 3DP models.
The students' performance showed enhancement and improvement in their ability to interpret anatomical features and structures in clinical images. A paired t-test showed that the improvements were highly significant (*P < 0.001) based on the post- and pre-test results.

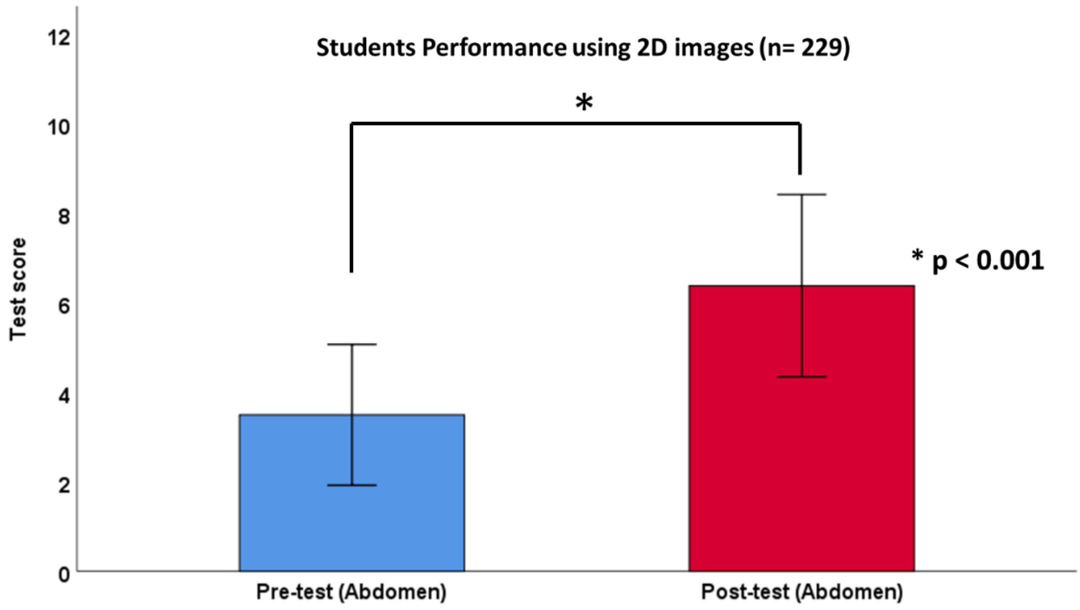


Figure 6.40. Students' performance when using 2D images.
A highly significant improvement (*P < 0.001) in student performance was observed when the students used 2D images.

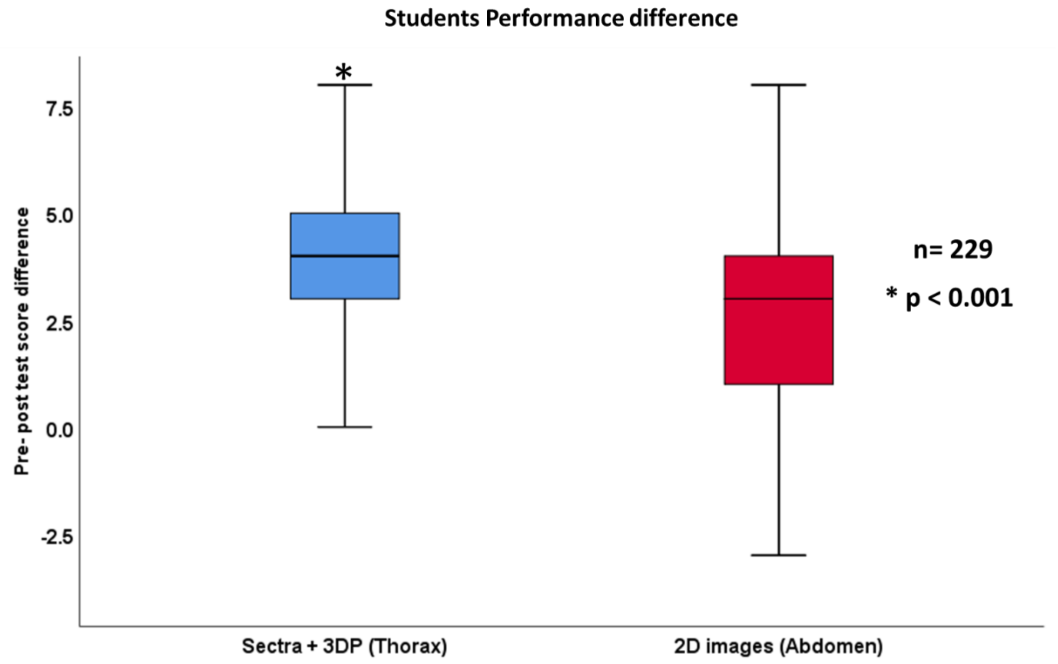


Figure 6.41. Comparison of performance for students using Sectra with 3DP models versus 2D images.
Box plot showing the differences in student performance calculated as the difference between the pre-test and post-tests results in both sessions. The levels of performance in the two sessions showed a highly significant difference (*$P < 0.001$). However, the difference in student performance when using the Sectra + 3DP models (mean = 3.8, SD ±1.8) was highly significant compared with the use of 2D images only (mean = 2.9, SD ± 2.1, n = 229).

6.2.8 Influence of MR ability on performance of medical students in cross-sectional clinical-image interpretation

In this part of the study, we investigated the relationship between the MR abilities of the students and their clinical interpretation performance using either Sectra + 3DP models or 2D images. Linear regression analysis was conducted to determine whether there were any correlations between the MR ability of the students and their performance.

Regression analysis to identify a relationship between the use of Sectra + 3DP models and MR ability

Regression analysis demonstrated a very weak positive correlation ($R^2 = 0.053$) between student (n = 96) performance using Sectra + 3DP models and MR test scores, as shown in **Figure 6.42**. These results suggest that MR ability does not predict a positive performance in interpreting clinical images and vice versa.

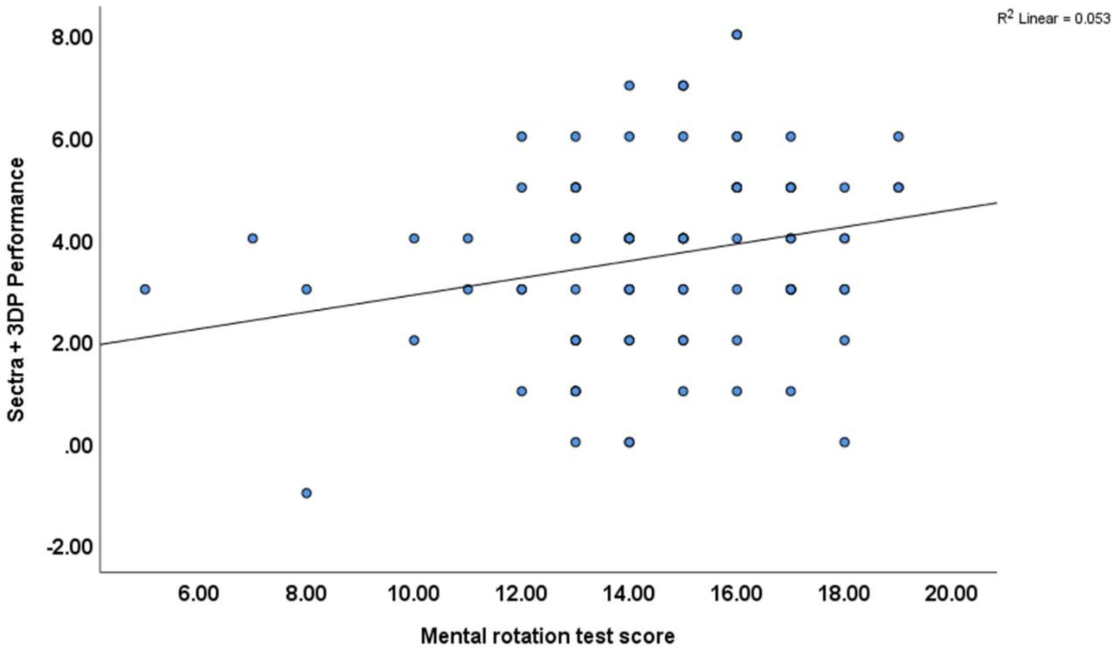


Figure 6.42. Regression analysis to identify a relationship between a student's performance using Sectra + 3DP models and their mental rotation ability.
A very weak positive correlation was shown by the results between Sectra + 3DP performance scores and mental rotation test results. (n = 96)

Regression analysis to identify a relationship between the use of 2D images and MR ability

The same regression analysis was performed to identify a relationship between the use of 2D images and MR ability. The results showed a very weak negative correlation (R^2 = 0.001) between the students (n = 96) performance using 2D images and their MR ability test scores (**Figure 6.43**), suggesting that there is no relationship between a student performance using 2D images and MR.

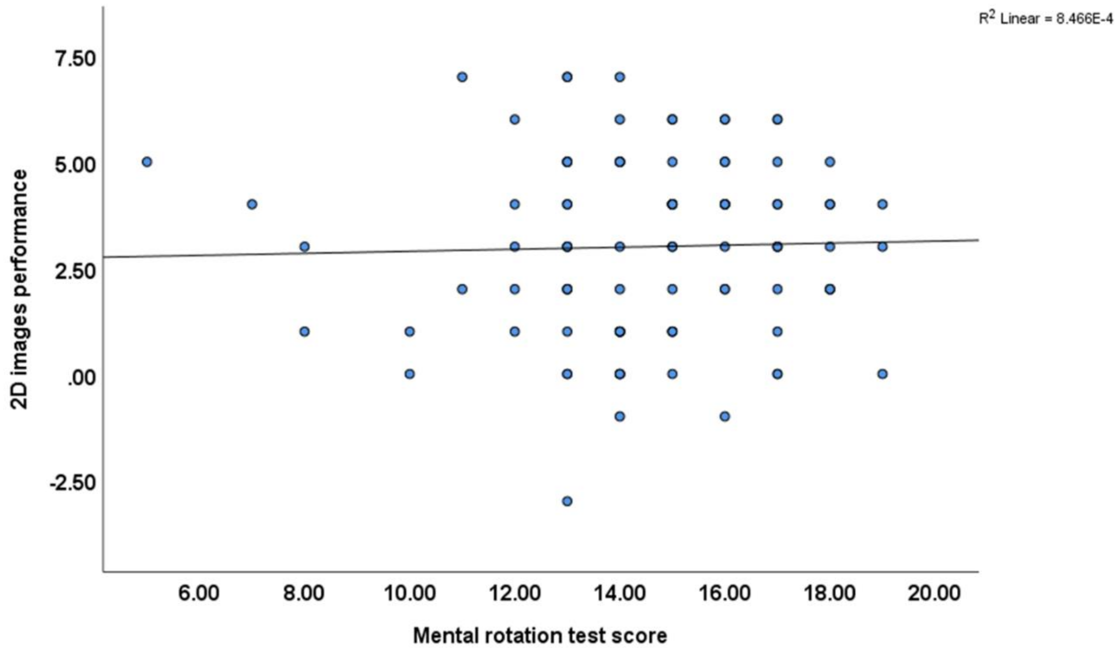


Figure 6.43. Regression analysis to identify a relationship between a student's performance using 2D images and their mental rotation abilities.
The results shown a very weak positive correlation when comparing 2D image performance scores and MR ability test scores. (n = 96)

6.2.9 Concepts and themes arising from a focus group analysis with first-year MBBS students of the 2018/2019 academic year

Three first-year medical students (MBBS) participated in the focus group to provide their insights about human anatomy learning at MSNU. The students were asked general questions regarding the challenges they faced when they studied anatomy and how the anatomy teaching could be improved. The group discussion was voice recorded and transcribed verbatim. The data from the focus group were then subjected to thematic analysis, which revealed emerging themes and concepts. The themes and concepts were then verified by the supervisor to ensure a blind check and double coding.

Theme 1: Complexity, volume, and distribution of content

Participating students reported that the volume of content and contact time are the main reasons that make anatomy hard to learn. They complained that amount of materials was too large considering the lecture time. The volume and the distribution of the content are considered the main reasons that made anatomy challenging, and the reduction of the contact time is the reason of that:

"*It is not necessarily ridiculously complex, it's just so much to learn."* (Participant A)

"The same embryology is really hard as well." (Participant A)

"Yeah, embryology is so hard." (Participant C)

"I Close up and actually inside, histology was a lot more complicated." (Participant A)

"I feel like CT was really hard before they actually gave us anything. It's just really really tricky" (Participant B)

Theme 2: Prior knowledge and preparation

The students also mentioned that prior knowledge is essential for enhancing anatomy learning for medical students:

"You feel like you almost got that confidence because you know it." (Participant A)

"I think you have to have some kind of pre-existing knowledge before you go into it; otherwise, it's just sort of a lot." (Participant A)

Theme 3: Basic knowledge and context/scaffolding

Participants reported that landmarks are one of the essential factors that will help the students connect the anatomical structures and body systems. One individual stated that*:*

"If you know the landmarks of what's supposed to be happening, then you can kind of go yes I can figure it out." (Participant B)

Theme 4: Time on task

The time given for the lectures and the practical sessions was not enough to cover all the details. Although the anatomy department used many resources to enhance anatomy learning, the first-year medical students find the reduction in the content time to be a struggle for them. Overall, these comments indicated that the time on the task is one of the primary reasons why students struggle when they study anatomy:

"I would struggle massively with all of that for the heart in one week, then the thing is that they gave us, let's say, something six times as hard as the heart in the same time that you had to learn the heart and that's the problem." (Participant B)

"We need more time for everything," (Participant B)

"Sometimes it does feel quite rushed." (Participant C)

Theme 5: Self-directed learning

The majority of the participants had a positive perception of using the new resources to improve their anatomy learning. The students mentioned during the discussion that the self-directed resources helped them while studying anatomy. The Sectra was a helpful resource that was a common view amongst interviewees, especially with clinical imaging interpretation. The 3D printed models' properties, including detail, size and colour were referred by the students. These properties of the 3D models were essential for anatomy education. The first-year medical students recommended some self-directed learning resources such as Videos, YouTube, Gray's anatomy and VH Dissector:

"I find it actually easier with self-directed learning." (Participant C)

"I think Sectra was the best thing in the world." (Participant B)

"So with the Sectra, I think sometimes some of the pictures we get there actually are nice." (Participant B)

"Giving you the three planes as well, that was amazing." (Participant B)

"So having that 3D model and that much detail is not as helpful as maybe other models." (Participant A)

"I think you should do more links to videos to be more helpful." (Participant C)

"I keep watching YouTube videos on what things look like." (Participant C)

"Yeah even if it's YouTube, there is some amazing YouTube you can get." (Participant B)

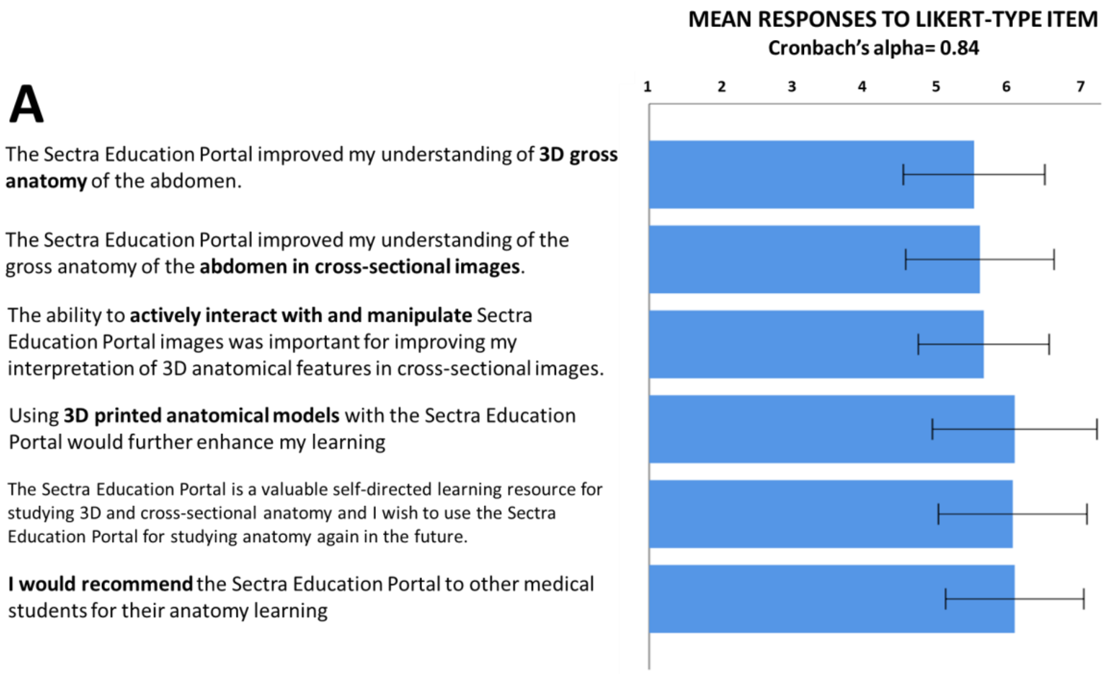
"Like Gray's Anatomy book for me, it's just got everything." (Participant B)

6.3 Phase III: Investigating Remote Multimodal 3D Anatomy Learning

Students' perceptions of the value of remote multimodal 3D resources and how they impact the most challenging areas of anatomy learning were sought. Statistical analysis of student answers to Likert-type questionnaire items and thematic analysis of focus group transcripts are presented.

6.3.1 Perceptions of MBBS students regarding SEP usage

During the 2019/2020 and 2020/2021 academic years, first-year medical students completed the SEP usage questionnaire (**Table 5.10**). The questionnaire is provided in the appendix. In the 2019/2020 academic year, 38 students completed the questionnaire after they used the SEP for the abdomen case **(Group 1)**. In the 2020/2021 academic year, 28 first-year MBBS students completed the same questionnaire after they engaged in a compulsory case about the thorax **(Group 2)**. The student perceptions of SEP usage were identified by responses to Likert-type items **(Figure 6.44)**. Overall, the responding students from both years reported that using the SEP was useful and effective for learning and understating gross anatomy and cross-sectional clinical-image interpretation for the abdomen and thorax. In general, the SEP features were useful for all participants and increased their ability and confidence to identify anatomical structures and features in cross-sectional images.



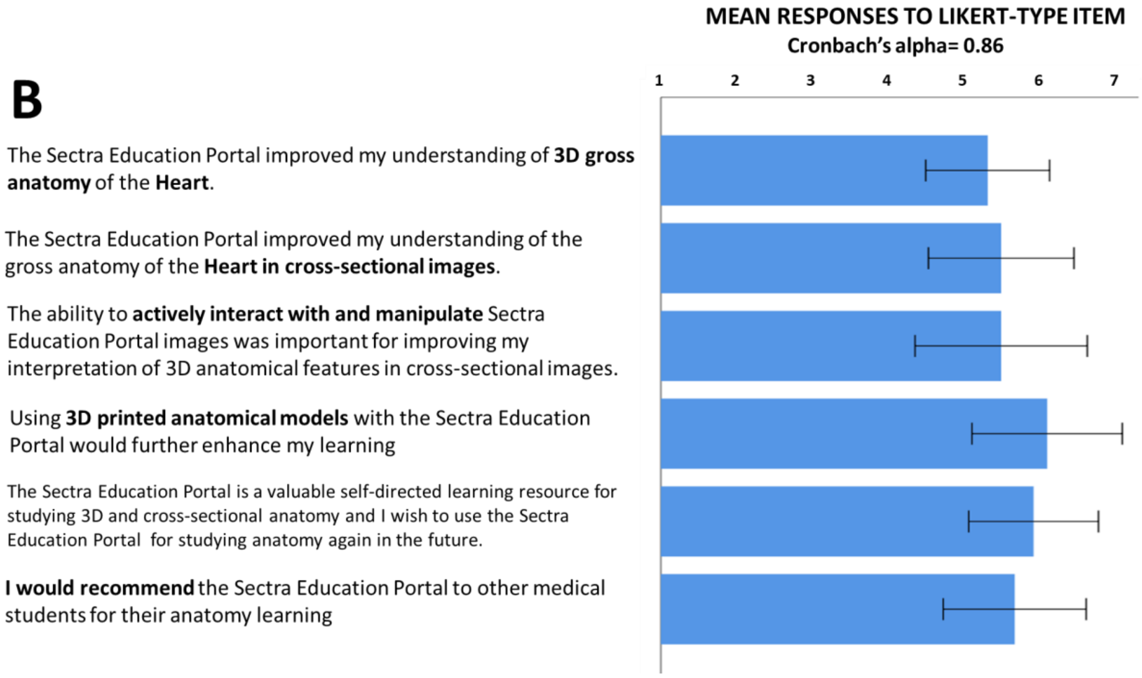


Figure 6.44. Students' perceptions of SEP usage.
(A) Overview of the perceptions of first-year MBBS students (n = 38) regarding SEP usage for the abdomen case during the 2019/2020 academic year. Interactions with SEP features (mean = 5.58, SD ± 1.08) improved the students' interpretation of 3D anatomical structures and features in cross-sectional images. Participant responses indicated an overall agreement that both SEP (mean = 6.08, SD ± 1.04) and 3DP models (mean = 6, SD ± 1.32) were valuable self-directed remote resources. (B) In the 2020/2021 academic year, 28 first-year medical students completed and returned the same SEP questionnaire for the thorax. The results obtained from the questionnaire were similar to those from the previous year, even though the anatomical region was different. The students gave positive feedback regarding SEP usage and their improvement in anatomical learning.
Likert-type items scale: 1 = strongly disagree and 7 = strongly agree.

6.3.2 Themes arising from free-text comments regarding interactions with the SEP

First-year medical students from 2019/2020 (Group 1) and 2020/2021 (Group 2) were asked the following free-text item from the questionnaire: *Please describe why your interactions with the SEP were/were not important in enhancing and improving your understanding of 3D and cross-sectional anatomical features* (**Figure 6.45**). Most of the participants from both groups completed the free-text item, and five themes arose from the analysis. Overall, 28% (n = 7) of respondents from Group 1 (year 2019/2020) indicated that the SEP was important for visualizing anatomical structures (**Figure 6.45A**): *"It helped me visualise the size of the intended anatomy." "I think it helped for me to visualise, and I think it helped as I struggled with cross-sectional imaging." "It helped with visualising anatomy."* Understanding the 3D structure, connecting points and structures, improving clinical-image interpretation, and employing useful resources were themes that developed from the semi-quantitative thematic content analysis of free-text answers for Group 1 (2019/2020) (**Figure 6.45A**).

When the participants from Group 2 (2020/2021) were asked to respond to the same free-text item, a minority of participants (21%, n = 6) indicated that the SEP improved their visualisation skills (**Figure 6.45B**): "*It was a very useful resource for visualising structures*." "*I found it easier to visualise the 3D structures, and I was able to see different viewpoints.*" "*It allowed me to visualise the anatomy of the patient and orientate myself.*" The comments showed that the SEP was important for enhancing and improving 3D understanding, and the comments were obtained from 21% (n = 6) of the responding cohort: "*At the end of the day, we will be dealing 3D patients, not 2D colourful diagrams, as a doctor, and I believe that Sectra allowed me to grasp a greater understanding of the 3D structure of the heart.*" "*Sectra allowed me to see the anatomy in 3D and develop a better understanding as to how the structure may look in the body.*" Moreover, 18% (n = 5) of the responding cohort indicated that the SEP enhanced their clinical-imaging interpretation: "*As a completely new topic to me, exposure to as many clinical images as possible, as provided with Sectra, is key to improving my understanding.*" "*It was important, as it introduced me to the features that could be viewed in transverse planes as well as increased my familiarity with CT scans.*"

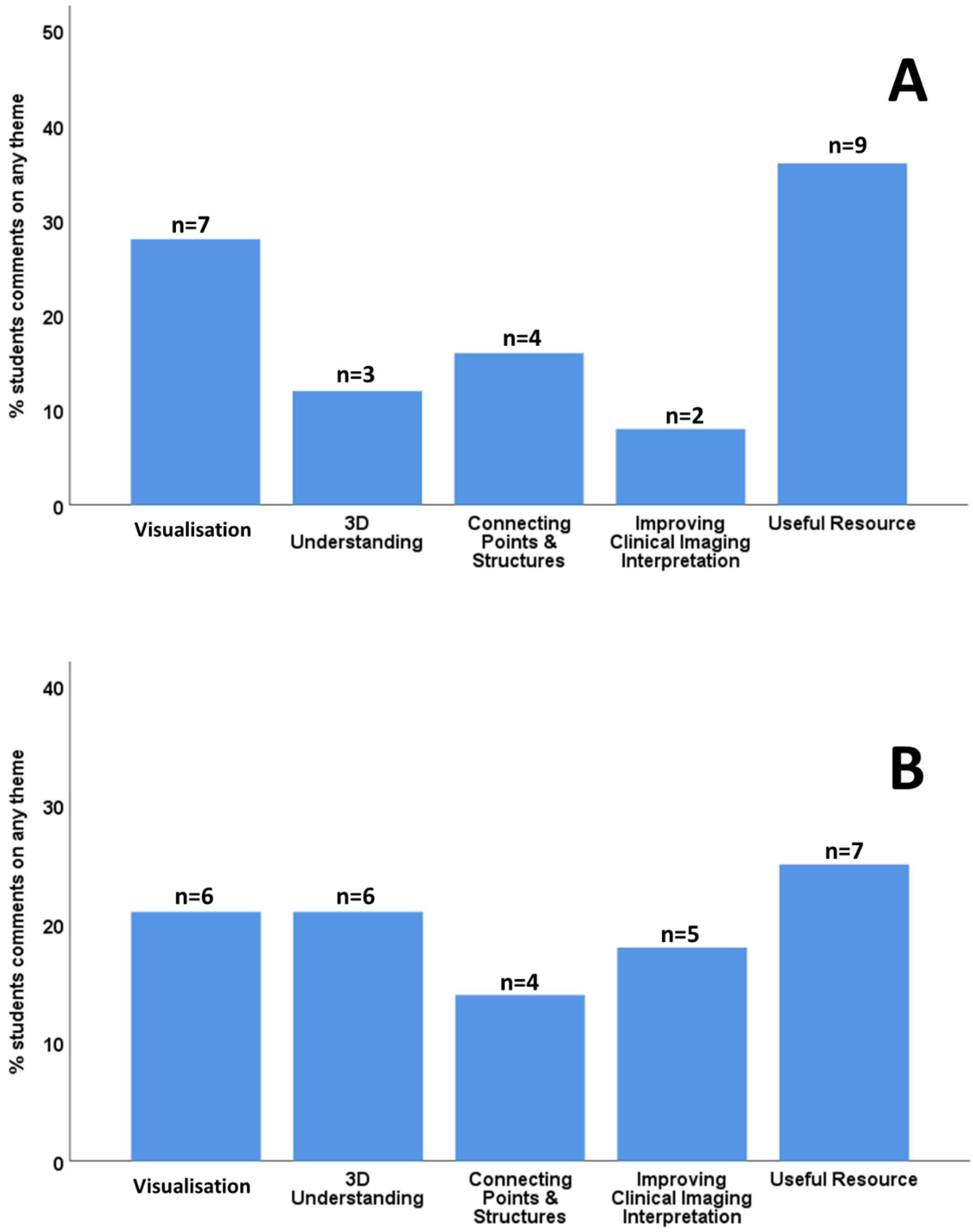


Figure 6.45. Themes arising from free-text comments regarding the benefits of interactions with the SEP.

(A) Themes arising from semi-quantitative thematic content analysis of comments from Group 1 (n = 25) (2019/2020) regarding interactions with the SEP. (B) Themes arising from semi-quantitative thematic content analysis of comments from Group 2 (n = 28) (2020/2021) regarding interactions with the SEP.

6.3.3 Importance of a touchscreen in improving students' understanding of anatomical features in 3D images

In this section of the questionnaire, the students from both groups were asked whether the touch option of the SEP improved their understanding of anatomical structures and features in 3D images and clinical cross-sectional images (**Figure 6.46**). Some students reported that the touch option was user-friendly and useful, while others found it overly sensitive and hard to use (**Figure 6.46**).

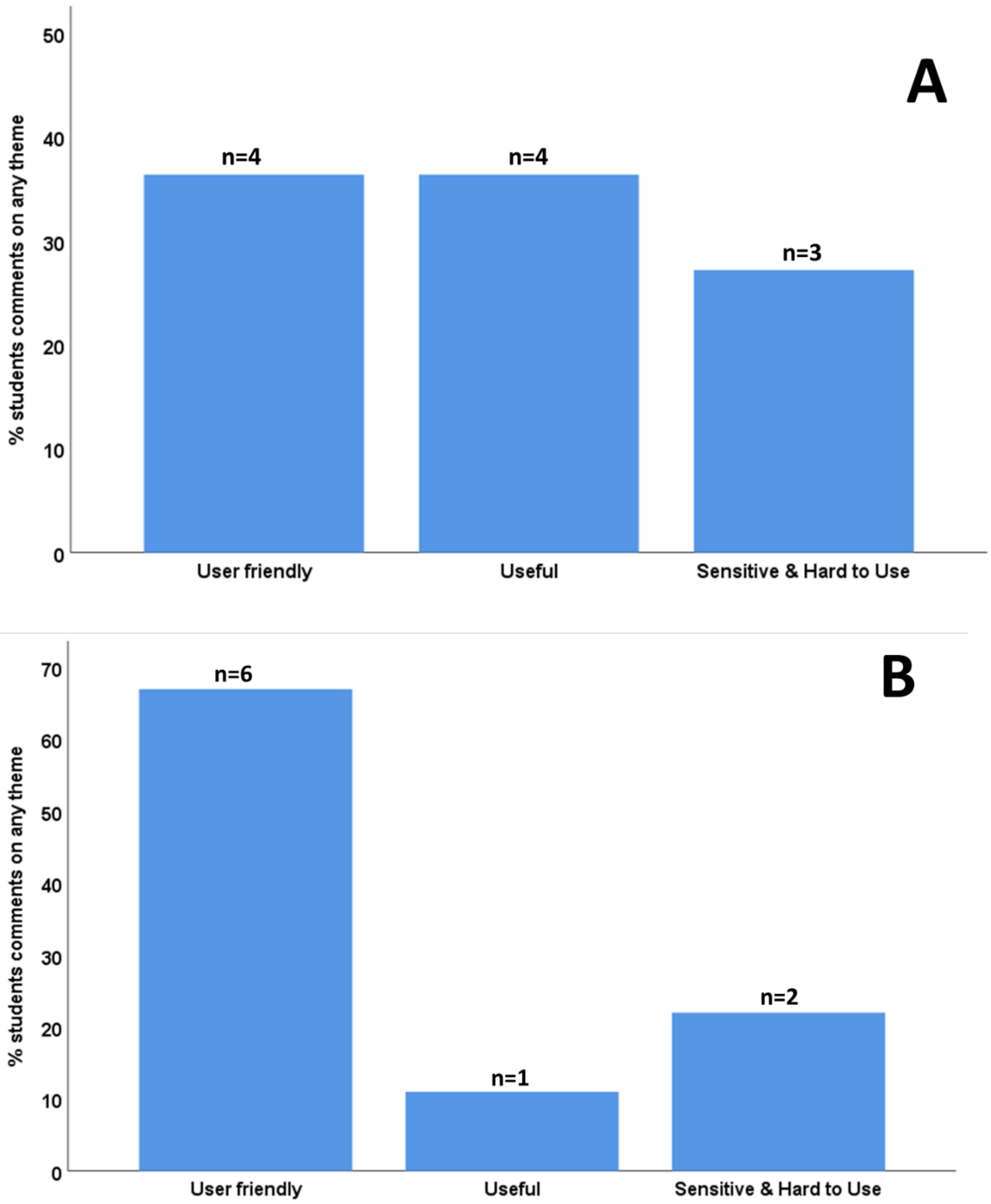


Figure 6.46. Student perceptions of the touchscreen option of the SEP.
(A) Results for Group 1 (2019/2020) (n = 11). (B) Results for Group 2 (2020/2021) (n = 9).

6.3.4 Other self-directed anatomy and clinical image resources used by the participating students to study and learn anatomy

To identify resources other than the SEP used by the students to study and learn anatomy, participants were asked to respond to the following free-text item from the questionnaire: *Please describe any self-directed anatomy and clinical imaging resources (other than the SEP) that you currently/previously used in your own time for study or revision (outside of time-tabled teaching)* (**Figure 6.47, 6.48**). A number of resources were identified by analysing the students' responses, including books, websites, and applications.

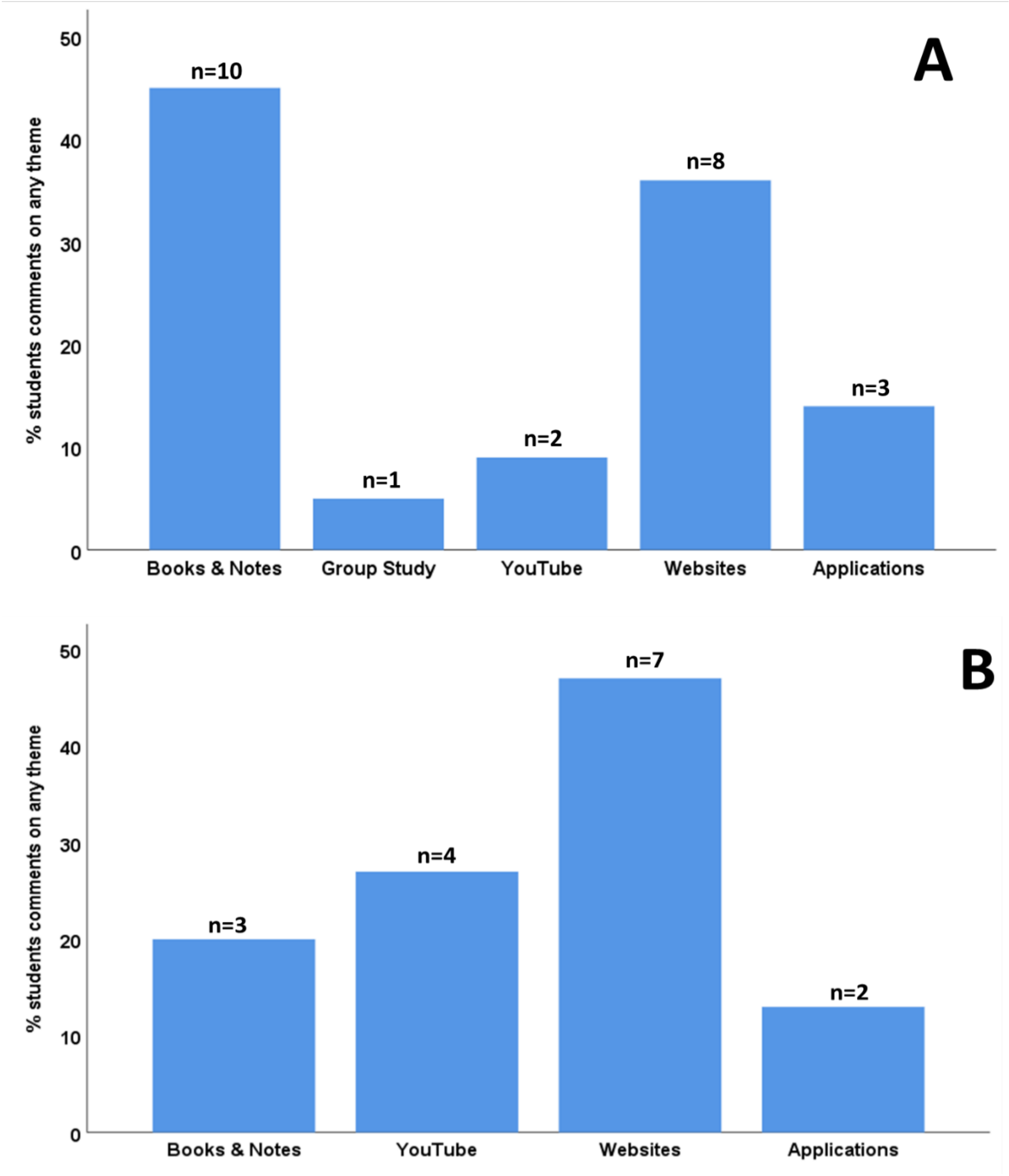


Figure 6.47. Themes arising from free-text comments regarding self-directed anatomy resources used by the students to study on their own time.

(A) In Group 1 (2019/2020, n = 24), 41% (n = 10) of the students used books and notes as a self-directed learning resource to study **anatomy** on their own time. The remainder of the students used YouTube, websites, and applications for studying. (B) Themes arising from semi-quantitative thematic content analysis of comments from Group 1 (2019/2020, n = 16) regarding resources they used to study **clinical images**.

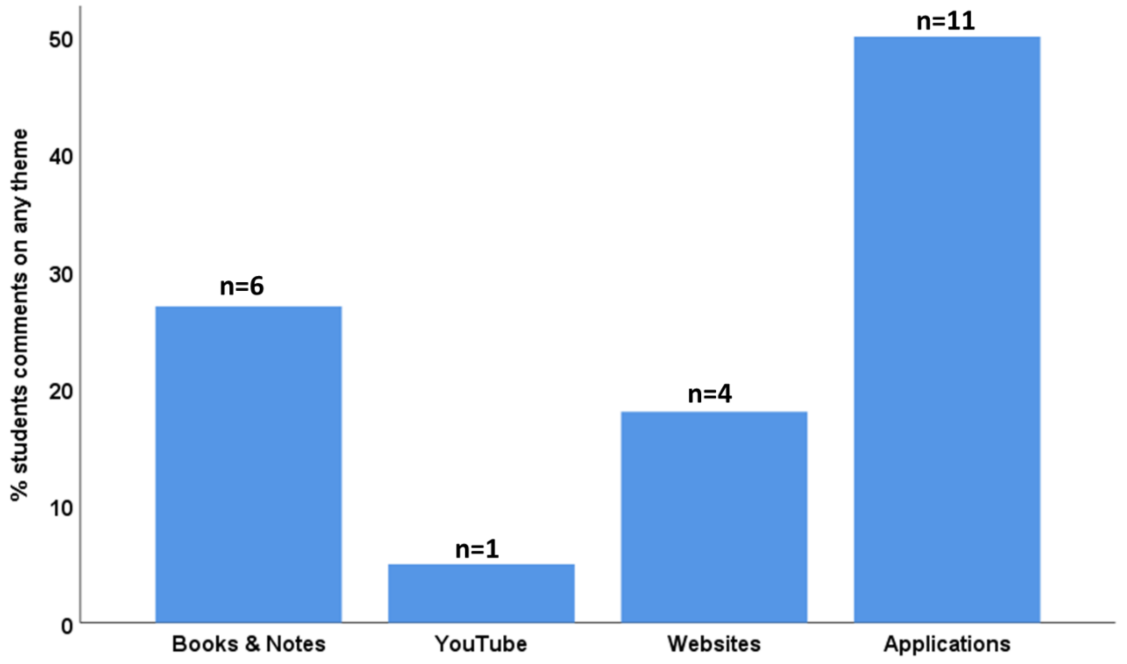


Figure 6.48. Themes arising from free-text comments regarding self-directed anatomy resources used by students to study on their own time.
Themes arising from semi-quantitative thematic content analysis of comments from Group 2 (2020/2021, n= 22) regarding self-directed resources used by students to study **anatomy and clinical images** on their own time. In this group, 50% (n = 11) of the respondents used different applications, such as Complete Anatomy, to study anatomy and clinical images.

6.3.5 Suggestions for improving SEP usage

In the last section of the questionnaire, both groups were asked to provide suggestions on how to improve SEP usage to enhance anatomy learning. Group 1 (2019/2020) suggested the addition of more labelling and more annotated CT scans as well as more detailed tutorials (**Figure 6.49A**). A participant from Group 1 (2019/2020) suggested that the SEP should be used in the DR. Analysis of comments from Group 2 (2020/2021) showed a major theme in terms of quantity (n = 4, 44%) indicating that students felt that tutorials were needed for improving SEP usage (**Figure 6.49B**).

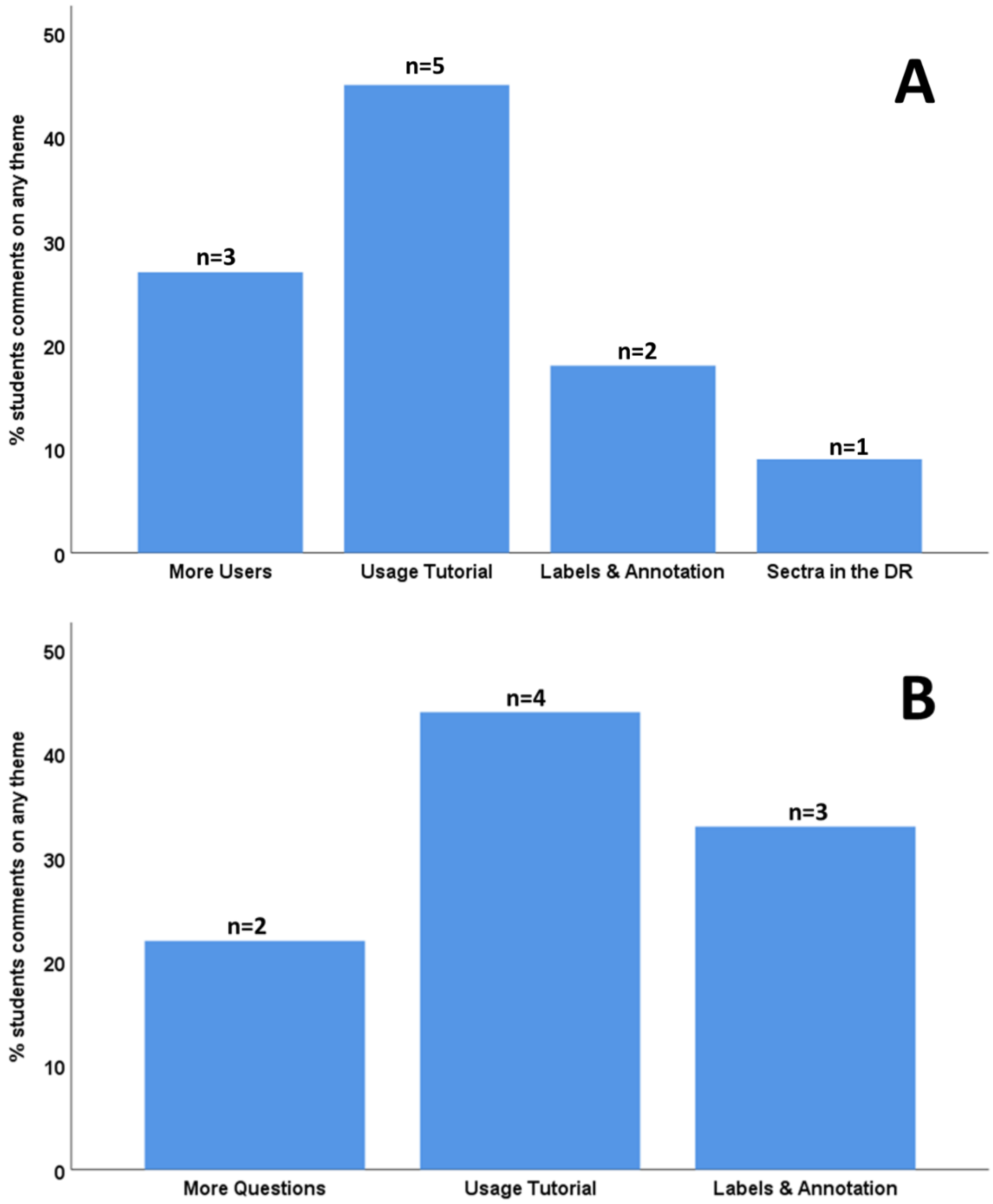


Figure 6.49: Themes arising from free-text comments providing suggestions for improving SEP usage.

(A) In Group 1 (2019/2020; n = 11), the participating students responded to this free-text item: *Please describe any other suggestions you may have for improving how we use SEP***.** Analysis of the free-text comments identified four suggestions from participants to help improve SEP usage. (B) Students from Group 2 (2020/2021, n = 9) suggested the use of more questions, more usage tutorials, and more labelled and annotated CT scans to improve SEP usage.

6.3.6 MBBS students' performance using Sectra and 3DP models and the SEP

Experimental tests were given to first-year medical students (MBBS) in the 2019/2020 academic year to assess their anatomy learning improvement and their ability to interpret cross-sectional clinical images (**Table 5.3**). In total, 114 (34% of the cohort, n = 330) first-year medical students participated in the quantitative part of this study. The students were tested on two anatomical regions during practical teaching sessions.

Comparison of pre-test and delayed post-clinical imaging test scores for students in a thorax practical session, determined by the mean test score of the participated students, showed a highly significant improvement ($P < 0.001$) (**Figure 6.50**), suggesting that Sectra and 3DP models improved the students' ability to interpret cross-sectional clinical images.

A pre-test and delayed post-test were administered to the same students in the abdomen session, where they used the SEP to interpret clinical images of the abdomen. At the beginning of the session, the students were given a pre-test (mean = 3.8, SD ± 1.5), and after a two-week period, the students took a delayed post-test (mean = 6.8, SD ± 1.8) (**Figure 6.51**). The improvement in clinical-imaging test scores between the pre-test and delayed post-test was highly significant ($P < 0.001$) based on a paired t-test (**Figure 6.51**), indicating that the SEP enhanced the students' skills and abilities to interpret clinical cross-sectional images.

The level of performance in the two sessions was calculated from the difference between the pre-test and delayed post-test for both the thorax (integrated and combined Sectra and 3DP models) and abdomen (SEP) sessions. Boxplots and a t-test indicated no significant difference in the first-year medical students' performance when comparing the use of Sectra and 3DP models with the use of the SEP (**Figure 6.52**). These results indicate that all resources used for both practical sessions are effective resources for improving student interpretation of clinical images.

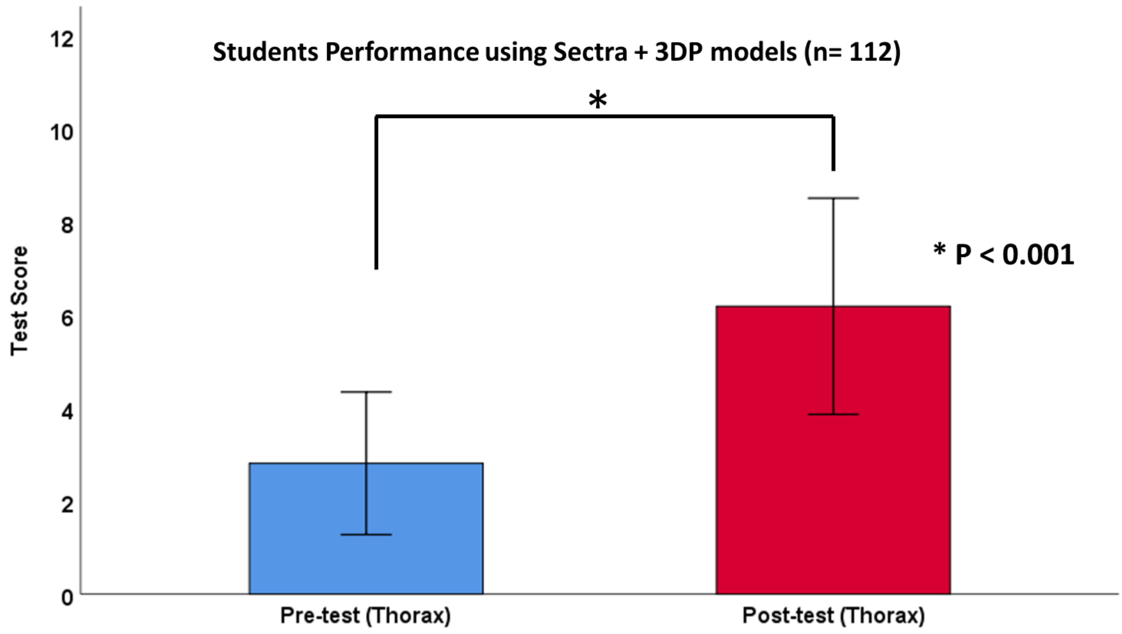


Figure 6.50. Students' performance when using Sectra + 3DP models in the thorax session. The performance of students (n = 112) showed an improvement in the students' skills and abilities to interpret anatomical features and structures in clinical images. A paired t-test showed that the improvement was highly significant (*P < 0.001) for the post-test results when compared with the pre-test results.

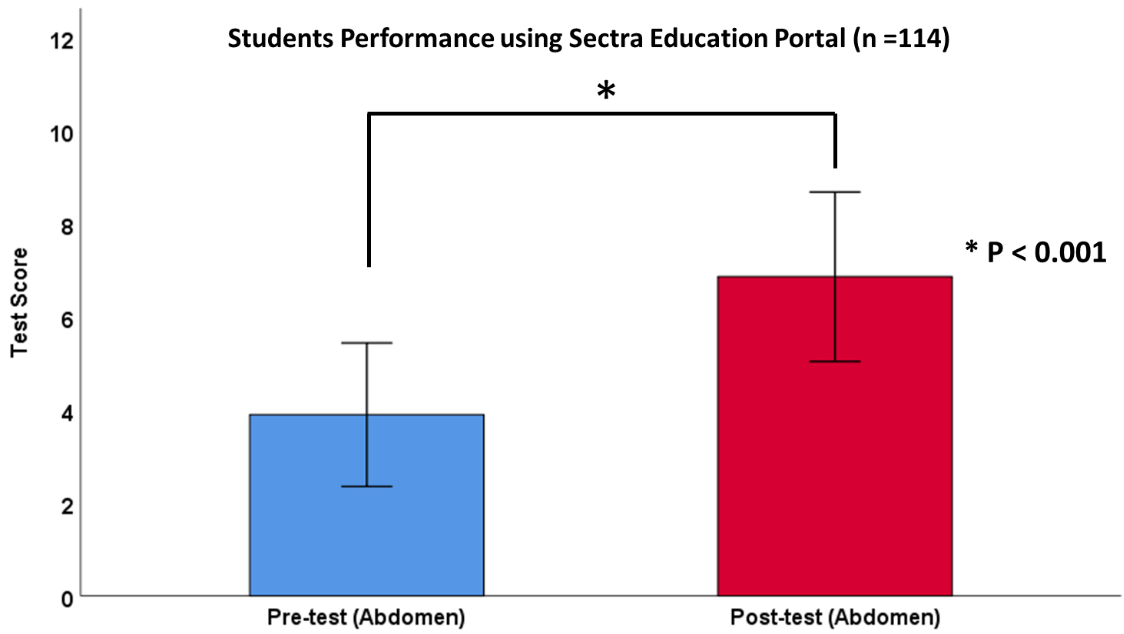


Figure 6.51. Student performance when using the SEP in the abdomen session. A highly significant improvement and enhancement (*P < 0.001) was observed in the students' performance (n = 114) when they used the SEP.

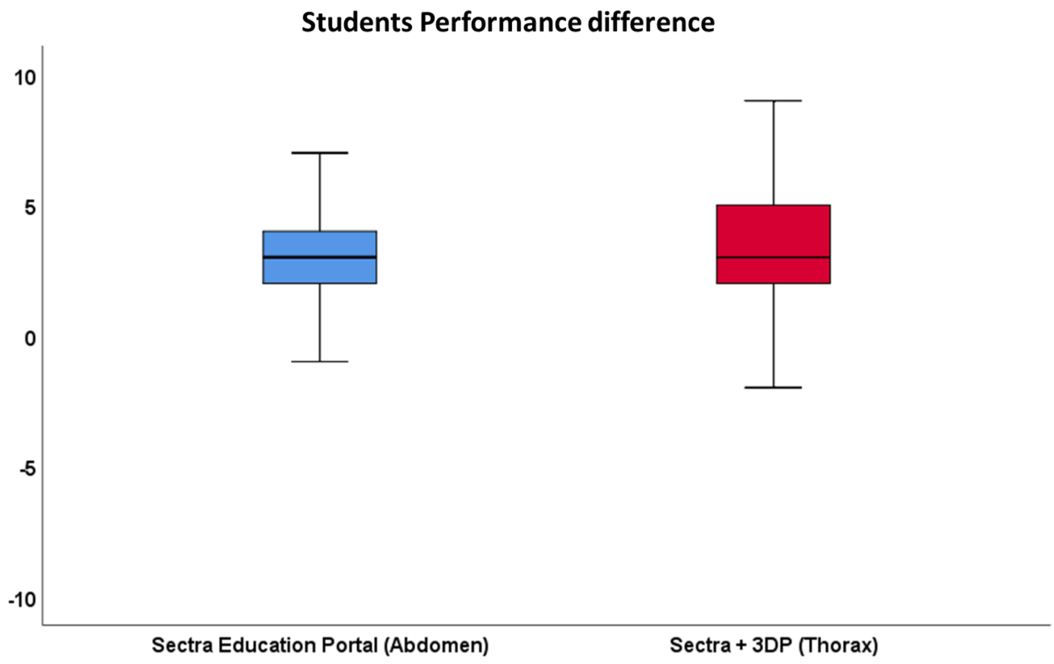


Figure 6.52. Comparison of performance for students using the SEP versus Sectra with 3DP models.
A box plot and t-test showed no significant difference in clinical-imaging test performance between students using the SEP versus Sectra with 3DP models (n = 112).

6.3.7 Concepts and themes arising from a focus group analysis with first-year MBBS students from the 2019/2020 academic year

A focus group was conducted with first-year medical students enrolled in the five-year undergraduate MBBS medical program at Newcastle University in the 2019/2020 academic year. Students who had registered for the anatomy course were invited, and four students attended the focus group session. The one-hour discussion session was recorded, and verbatim transcription was performed. Thematic analysis was used to analyse the transcript, and concepts and themes were identified.

Theme 1: Spatial awareness and 2D-3D understanding

It was mentioned in the discussion by the students that the 3D images and the 3D resources enhanced their understanding of anatomy understating, especially with challenging topics such as clinical imaging. Spatial awareness and visual awareness, which are understanding the relationship between different structures and knowing the location of each organ in relation to other organs, were important for the students to study anatomy, as the student stated:

"It wasn't enough for us to be able to basically transform those 2D structures that we had in mind into CT scans." (Participant B)

"It's a lot easier to picture what's actually going on when you see 3D figures instead of 2D because 2D is very limited." (Participant B)

"*Spatial awareness is pretty special."* (Participant D)

"I think visual awareness is what I think it's important." (Participant A)

Theme 2: Learning resources

The details of the 3D printed models were an issue mentioned in the discussion where some of the students found that the models lacked the perfect details, especially when they compared them with the other models or the real specimen in the dissection room (DR). However, the 3D printed model was perfect for the external structures of the anatomical structures. The students had a positive perception when we discussed the usage of the Sectra during the practical session. The majority commented that they liked the SDL resources that helped them in learning anatomy:

"I did not find that particularly useful, like holding it, especially when you are about to hold like a real heart." (Participant D) (students responding to the value of 3DP models)

"I guess that would be useful for the external anatomy." (Participant D) (student response to the value of 3DP models)

"I feel like for that lecture, yes, it was useful." (Participant B) (student response to the value of 3DP models)

"I feel like I just use the ones that the university offers, as well as like YouTube videos, because I find them quite useful." (Participant B)

"*After I looked at videos and started using like this Sectra thing, it became a lot easier."* (Participant B)

"I thought it was a really useful resource [Sectra]." (Participant B)

"I actually like to use the apps." (Participant C)

"I find it [Sectra] very useful, as I can see the location of structures in relation to others." (Participant D)

"I found Sectra useful, depending on when you do it in the session." (Participant D)

Theme 3: Terminology and complexity

Embryology is considered to be one of the challenging topics for the students. The detailed development stages of the embryo were hard for some students to understand. The new terms and terminology were another challenging area of anatomy that the students needed help with. The amount of these new terms was hard to memorise and remember, as some of the students mentioned in the discussion*:*

"I don't really like embryology. I really didn't like it, and it was just a struggle." (Participant B)

"I think, in general, which I think all of the new terms like new names, and it was kind of a struggle to remember those, and I feel that when we learned anatomy, we had a lot of new things at once." (Participant A)

"Sometimes I find identifying different structures is a bit difficult." (Participant C)

Theme 4: Cognitive load and memorisation

Almost all the participants commented that the content volume was a lot for them. The students struggled with studying all the materials given to them because they had difficulty studying all that amount in a short period of time. As the cognitive load increases with the volume of the materials, the students depend on memorisation to study anatomy:

"*I feel that when we learned anatomy, we had a lot of new things at once; sometimes I struggled to take it all."* (Participant A)

"We always stress about anatomy, all we have to memorise, every single thing." (Participant B)

"Maybe we could have another DR session for people who struggle." (Participant D)

"I think we need to get more time because we already get an hour and a half." (Participant D)

"Just most importantly, more frequent DR sessions; that is the main thing." (Participant C)

"I liked it better when they would go through everything with us, rather than just leaving it up to us to ask them." (Participant B)

"It's pretty straight forward in a sense, where you just have to memorise and remember, you don't need like an application in anatomy. I think it's just memorising and understanding." (Participant B)

6.4 Phase IV: Digital Embryology Resources

During the COVID-19 pandemic, we provided the students with digital embryology resources to enhance their learning of embryology topics. The purpose of this section was to understand the benefits of digital embryology resources when blended into the anatomy course, using Likert-type questionnaire analysis and focus group analysis.

6.4.1 MBBS students' perceptions of digital embryology resource usage (HDBR digital heart models and interactive PDFs)

Our previous research results indicated that embryology was likely to be a challenging concept for second-year medical students (2MBBS-17/18) at MSNU (**Figure 6.1**). Digital embryology resources were introduced to the students to improve their embryology learning. The digital embryology resources included the HDBR and the Sectra interactive 3D-PDFs. First-year medical students from the 2020/2021 academic year (**Table 5.3**) were asked to complete the Embryology of the Heart tutorial guide by using the new digital embryology resources (HDBR digital heart models and interactive 3D-PDFs). The students were provided a link to a Likert-type questionnaire (**Table 5.11**) at the end of the tutorial guide to gather their views on the usage of digital embryology resources. Student responses to Likert-type items indicated that digital embryology resources were useful and improved their embryology learning and understanding **(Figure 6.53)**.

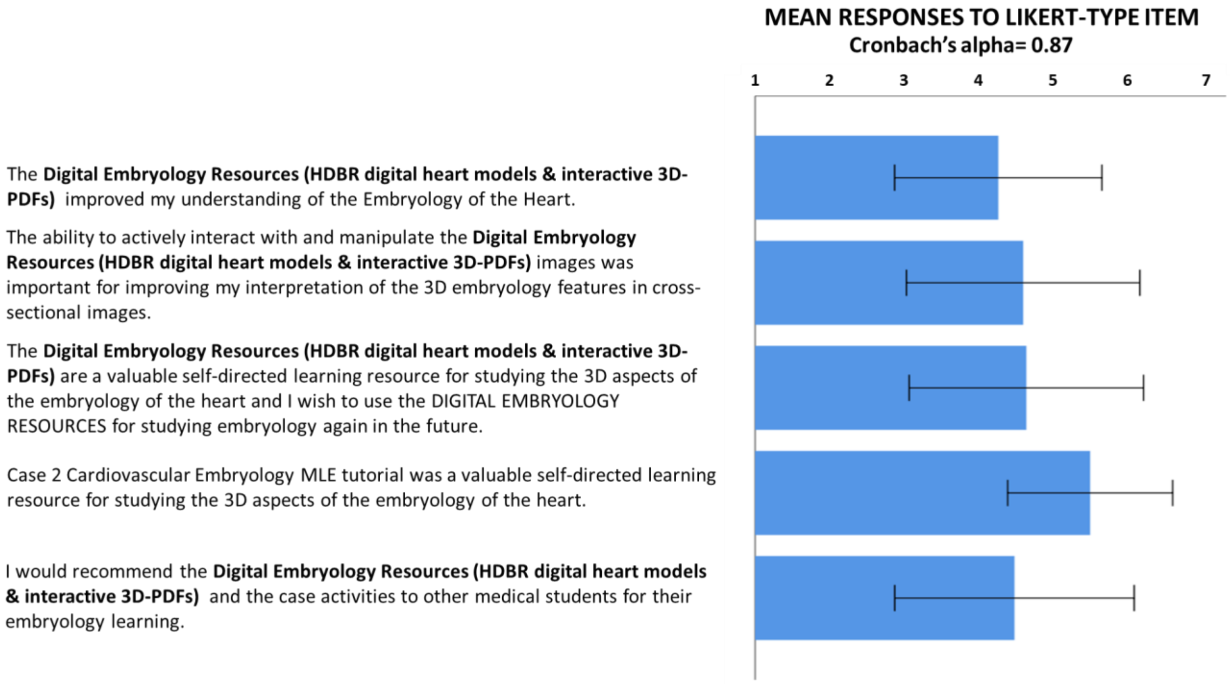


Figure 6.53. MBBS students' perceptions of using digital embryology resources (HDBR digital heart models and interactive PDFs).

Likert-type items in the questionnaire addressing the value of using digital embryology resources (HDBR digital heart models and interactive 3D-PDFs) to improve embryology learning. Likert-type scale in the questionnaire: 1 = strongly disagree, 7 = strongly agree (a mean value above 4 and response rate above 50% indicates overall agreement on the item statement). Overall, 69 responding students (21% of the cohort, n = 330) found that the digital embryology resources improved their understanding of heart embryology. The students agreed that the digital embryology resources were useful for studying the 3D aspects of the embryology of the heart (mean = 5.5, SD ± 1.1).

6.4.2 Themes arising from free-text comments regarding interactions with digital embryology resources

Having identified the added value of the digital embryology resources for embryology learning in remote environments, it was critical to examine the student perceptions of the impact of such activities on their embryology learning. First-year MBBS participants (n = 69) responded to the next free-text item of the questionnaire: *Please describe why your interactions with the HDBR digital heart models were/were not important in improving your understanding of 3D and cross-sectional anatomical features of the heart* (**Figure 6.54**).

Comments indicating that the HDBR digital heart models were important for improving their understanding of embryo development were obtained from 36% (n = 25) of the responding cohort: "*It made it easier to visualise the relationship between the structures and parts of the growing embryo and how it changed over time.*" "*They were helpful for visualising the* *development of the heart throughout the stages.*" "*They were useful to see the different stages and how the heart developed.*" "*They helped me visualise the arrangement of different developing systems in the embryo, and the rotation feature enabled me to understand the anatomy in all directions and perspectives.*" (**Figure 6.54**)

Comments indicating that the HDBR digital heart models were important for improving the students' 3D understanding and visualisation of embryo development were gathered from 23% (n = 16) of the responding cohort: "*It makes it much easier to understand anatomy when seeing it in 3D rather than just 2D images*." "*It allowed us to see where the organs are arranged in 3D and the relative sizes of structures to gain a better understanding of the layout and organisation of the embryo as a whole*." "*It always helps to observe a structure digitally in 3D, especially if the said structure is 3D in real life. 2D pictures can sometimes be misleading.*"

Other respondents found the HDBR digital heart models to be difficult and overwhelming (16%, n = 11). Some students wanted more labelled models (9%, n = 6) and more guidance (16%, n = 16) **(Figure 6.54)**. It is important to note that some of the students' comments can be counted in more than one theme.

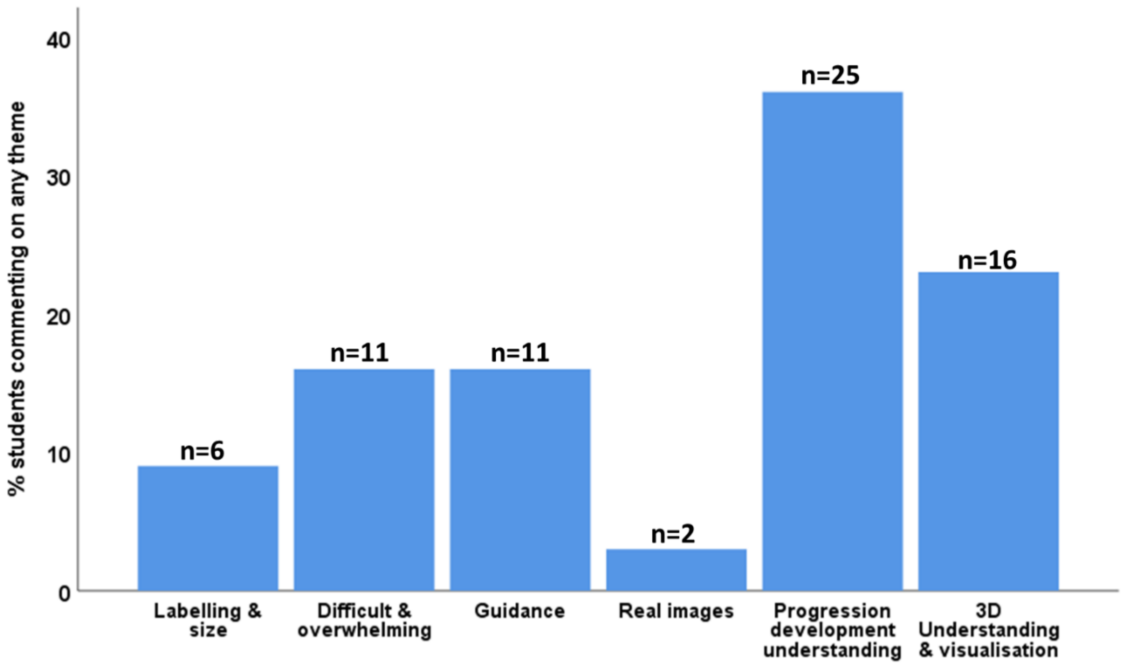


Figure 6.54. Themes arising from free-text comments regarding interactions with the HDBR digital heart models.

The same student cohort (n = 69) answered the following free-text item of the questionnaire: *Please describe why your interactions with the interactive 3D-PDFs of the heart were/were not important in improving your understanding of 3D and cross-sectional anatomical features of the heart.* From the responding cohort, 20% (n = 14) indicated that the interactive 3D-PDFs improved their understating of embryo development: "*It allowed me to explore the heart structure from different perspectives.*" "*Again, it aided in understanding or looking at the heart from different perspectives.*" "*They helped me understand the size and positioning and structures more easily*." "*The PDFs were useful, as they helped visualise the heart in relation to the development of other systems in the embryo and helped to see the size of the embryo at progressive Carnegie stages."*

Of the 69 participants who responded to this question, 12 (17%) reported that the interactive 3D-PDFs were a useful resource for embryology learning: "*The interactive elements were very important.*" "*They were very descriptive with their labelling and colours.*" "*The PDFs were easy to use and are a useful tool to refer back to and allow you to see all the structures together.*" "*The PDFs allowed me to isolate specific parts of the heart I wished to see, giving me greater insight into the internal structure of the embryonic heart. I found it very helpful*."

Some participants expressed that the interactive PDFs were difficult to use and overwhelming. Additionally, 21 of the participants mentioned that they faced a technical problem while using the interactive PDFs, which may be expected as the interactive 3D-PDFs were a new self-directed resource used by the students **(Figure 6.55)**.

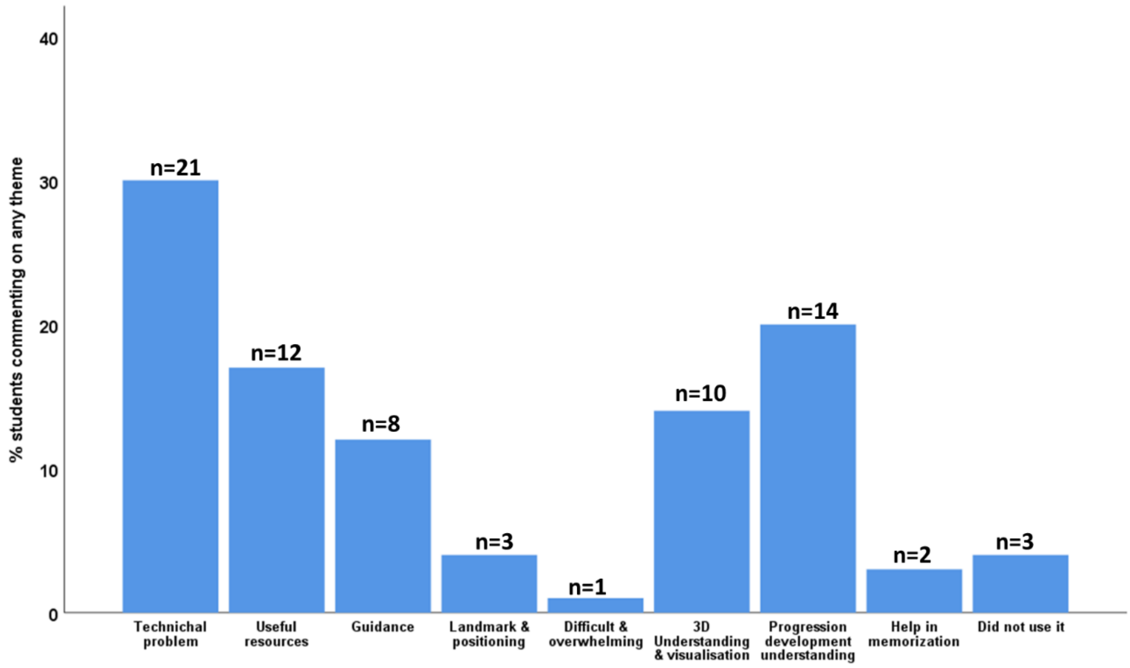


Figure 6.55. Themes arising from free-text comments regarding interactions with the interactive PDFs.
A total of 69 first-year MBBS students commented on a free-text item, and nine themes arose from a semi-thematic analysis.

The students were asked to respond to the following item*: Please describe any OTHER resources you used with the digital embryology resources (HDBR digital heart models and interactive 3D-PDFs) in order to complete any part of the activities in the Case 2 Cardiovascular Embryology MLE tutorial*. The students provided a range of responses (**Figure 6.56**). Among those who participated, 45% (n = 31) indicated that they used only the digital embryology resources to complete the activities in the MLE tutorial. The remaining students used other resources such as textbooks, tutorial guides, YouTube, and websites to complete the MLE tutorial (**Figure 6.56**).

The following themes were identified from the participating students' answers (n = 64) to the following item: *Please describe any other suggestions you may have for improving how we use digital embryology resources (HDBR digital heart models and interactive 3D-PDFs) in the future* (**Figure 6.57**). The students suggested that a more detailed guidance should be provided (42%, n = 27): "*Maybe a bit more guidance or demonstration in describing the models, as I found some of them quite hard to interpret on my own.*" "*Maybe by adding a recorded example of someone going through the diagrams quite closely and explaining some of the parts, as this would have made it easier to understand.*" "*Introduce the digital resources in live teaching where they can be explained, and then I can go back to them in my own time* *with a degree of understanding of what they show.*" The students also suggested using more labelled diagrams (8%, n = 5): "*I feel like there could be more labelled diagrams.*" "*It would be more helpful for the HDBR heart models to be labelled*." The students suggested making the resources easier to access (9%, n = 9): "*If you could put the 3D animations directly onto that MLE, the interface would be a lot easier and more accessible.*" "*Make them easier to access and use*." "*Perhaps make the information of development more accessible with the pictures, which were a little difficult to find.*"

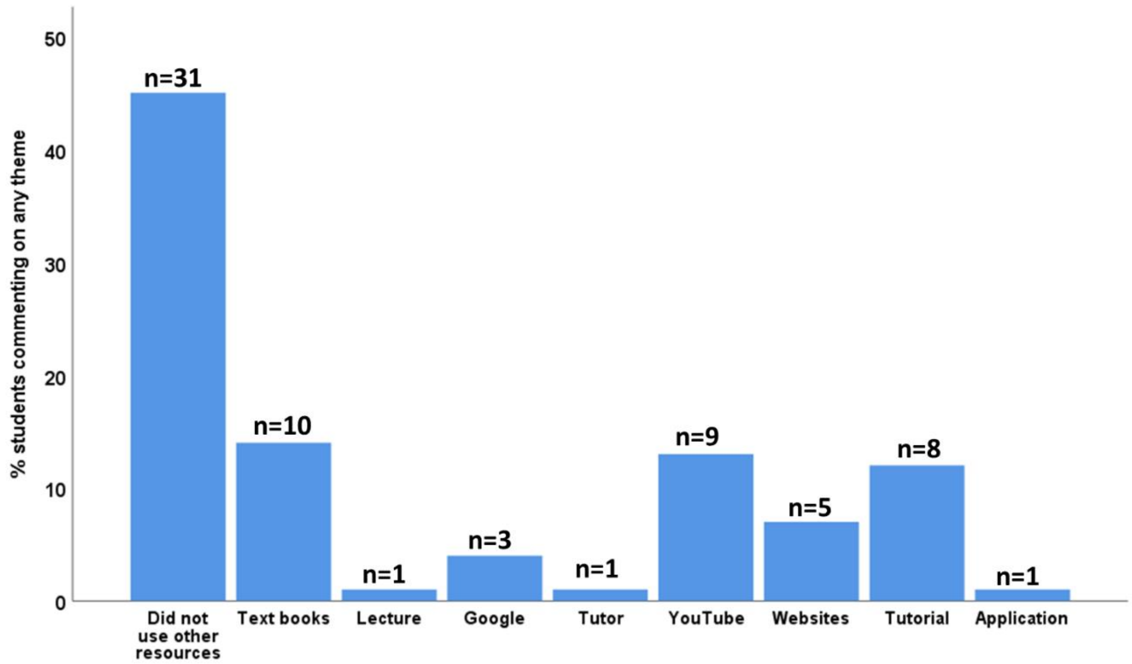


Figure 6.56. Emerging themes regarding any additional resources the students used with the digital embryology resources.
The additional resources that the students used beside the digital embryology resources to complete any part of the activities in the Case 2 Cardiovascular Embryology MLE tutorial (n = 69).

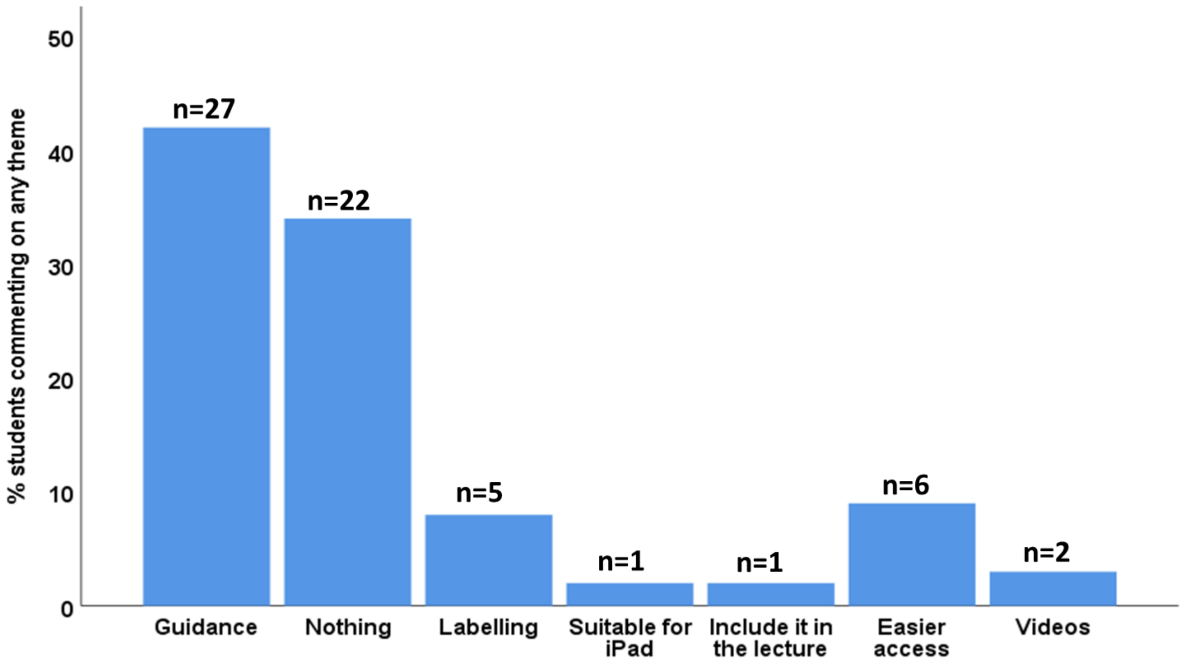


Figure 6.57. Themes arising from analysing student comments to the free-text item. Seven themes arose from the student suggestions for improving the use of digital embryology resources (n = 64).

6.4.3 Concepts and themes arising from a focus group analysis with first-year MBBS students from the 2020/2021 academic year

A focus group analysis was conducted to obtain more insights from first-year MBBS students regarding the difficulties they faced when studying anatomy during the COVID-19 pandemic and the benefits of self-directed learning resources. The focus group consisted of four students and was held online via Zoom for one hour. During that time, the students were asked to respond to and discuss questions asked by the moderator. The discussion was recorded, and the recording was later transcribed for analysis and evaluation. Concepts and themes were identified by analysing the focus group information and data. These concepts were further evaluated by thematic analysis (Braun and Clarke, 2006).

Theme 1: Communication

The students found it hard to communicate with the instructors and felt isolated during the COVID-19 lockdown. Most of the students explained that they could not communicate with their classmates to discuss small matters, which made them feel isolated and like they were on their own, unsure if their learning was correct or not. The students found it hard to them to ask questions as it will take days to get an answer back even for easy questions, and first-year medical students highlighted that:

"It got quite hard to communicate…It was quite hard, and it felt quite isolated at times." (Participant B)

"And I would agree on like it felt like really isolating" (Participant A)

"If you had, like, just a little question, which ordinarily would take like 30 seconds to explain, you wouldn't probably get the answer for a few days" (Participant C)

"It was quite hard to know what we were meant to be doing at what time, because we get like a lot of emails." (Participant B)

Theme 2: Complexity of structure and function

During the discussion, the students referred to several topics that they found challenging. The embryology of the heart was one of the major challenging areas. The orientation of the anatomical structures on the clinical imaging was complex for the students to understand at first, and that is why the students found clinical imaging to be challenging:

"Heart embryology was tough for me." (Participant C)

"But I think because the heart embryology was put together with basic embryology, like the first couple of weeks, like gastrulation interrelation, it was quite hard to understand all of that and then move on to the heart as well with the quick videos." (Participant B)

"I found that probably the clinical imaging is the hardest." (Participant C)

"I found the clinical imaging really hard as well, and from the MLE, there's not a lot of resources for those, like an example for each type of imaging." (Participant B)

"I think the hardest part was the clinical imaging." (Participant A)

Theme 3: Content of teaching materials

The students had a positive perception toward using the Digital Embryology Resources, as it helped them understand the 3D changes and developments of the embryo:

"I think it was very helpful to visualise stuff, especially with those little videos, where it shows you all around and then each different stage." (Participant A)

"Yeah, that really helped for the folding of the heart, because I was like, how does it go from this to something 3D?" (Participant B)

"I remember that really was helpful as well, that it had like many videos on lot of models." (Participant D)

"So, I think it was from case two, from the heart embryology. I found that really helpful as well." (Participant D)

"I find that quite helpful for like relationships between structures." (Participant D)

"Complete Anatomy gives you like definitions of what like this nerve does and where it goes, which is quite good, and you could take away layers so you could just see the vein, the nerve, and then you can add on stuff to see where it is in comparison, which was quite useful." (Participant B)

Theme 4: Flexible learning

The focus group thoughts that the self-directed learning resources were helpful in enhancing their anatomy learning and understanding, especially during the COVID-19 pandemic. The self-directed resources provided the students with the flexibility to use them on their own time:

"I think if we could have the self-directed stuff, because then it means that you can sort of work at your own pace." (Participant C)

"If you don't understand something, you've only got a set amount of time to learn it, whereas at least with the self-directed stuff, you can work through at your own pace." (Participant C)

Theme 5: Recommended Modifications

The students had some recommendations to enhance the usage of the self-directed learning resources:

"I just found it quite confusing to be able to see things on the pictures with what I knew, what it was, without much guidance on it." (Participant C)

"Well, I think they gave us like one username and password between two or three people, and so it was hard to coordinate who wanted it when because say you have different timetables for what we want to do in revision." (Participant B)

"I think it would be useful to have it not just in the case, like if it was like under the extra resources for the whole case rather than just in that one tutorial, it would be easy to remember to actually use it." (Participant B)

"I think it might be helpful as well, then we had a sort of short question at the end of the anatomy, but maybe have like a separate session, so, because I think a lot of the questions end up coming after the session once we don't have the chance to ask them anymore." (Participant C)

"I think the DR live session was the most useful part of what was given on the MLA and for lectures and seminars, and I think a lot of people were upset that it didn't happen straight away." (Participant B)

"I think personally, I just got really tired of looking at the screen so much, so I tried to like find resources like that wouldn't take me away from it. So I was trying to use my textbooks, like Gray's Anatomy and things like that." (Participant A)

Chapter 7. Discussion

This project was aimed at identifying the challenging topics in anatomy for medical students; implementing new digital and 3D resources in teaching anatomy; and finally assessing the effectiveness of these resources and their influence on the understanding and perceptions of students learning anatomy. After gross anatomy, imaging and embryology were identified as challenging areas in student learning. Thus, the implementation of new resources to enhance anatomy learning and understanding is important. Therefore, the perception and performance of MBBS and PA students were assessed through mixed methods in experimental, survey-based, and phenomenological (focus group) approaches, thus generating quantitative, semi-quantitative, and qualitative data under a post-positivist-pragmatist paradigm and a constructivist conceptual framework to investigate the effects of the introduction of digital and 3D resources on education.

7.1 Clinical Imaging, Embryology and Gross Anatomy are Challenging Topics in Anatomy Learning

A comparison of learner perceptions regarding clinical-image interpretation across topics in anatomical science education had not previously been performed. To develop and design the appropriate pedagogical methods and strategies to enhance student learning and education, the challenging areas and topics that students find most demanding in studying anatomy, as well as the underlying reasons, first needed to be identified. Survey results confirmed that students experienced challenges with respect to certain topics and concepts in studying anatomy.

7.1.1 Novice anatomy students experience learning challenges

Data analysis has shown that both PA and 1MBBS students had difficulties with certain topics in anatomy, particularly clinical-imaging interpretation. For first-year medical students (**1MBBS-18/19**), the anatomy of the thorax, followed by the anatomy of the abdomen, was their first experience in anatomy within their medical degree programme. At the time of the study, PA students had experienced introductory teaching on the anatomy of the thorax, abdomen, and limbs. The questionnaire data indicated that clinical imaging was significantly ($P < 0.05$) the most problematic topic for PAs (**Figure 6.12**) and was highly significantly more problematic ($P < 0.001$) for first-year medical students (**1MBBS-18/19**) than surface anatomy and gross anatomy (**Figure 6.19**). Both the PA and first-year medical student (**1MBBS-18/19**) cohorts found surface anatomy to be relatively less troublesome than gross anatomy. Clinical-image interpretation was found to be a source of difficulties for first-year medical students (**1MBBS-18/19)** in studying cross-sectional images (**Figure 6.19**). Therefore, learning activities must be designed, and the appropriate resources must be provided, to support students' learning and identification of the anatomical features and structures in cross-sectional images.

A potential source of difficulty may involve the transfer of learned information from one context to another. For example, first-year medical students have been found not to transfer visual information gained from clinical images or digital resources to the anatomical structures of the human body (Saltarelli et al., 2014; Cheung et al., 2021). This important concept should be considered in identifying how students transfer the knowledge gained from didactic lectures to real-world applications, such as understanding the location of the heart in actual human patients. This aspect may explain why novice students find clinical-imaging interpretation to be more challenging than second-year medical students **(2MBBS-17/18)** (**Figure 6.1**), in which knowledge transfer skills are better developed in experts than new learners (Norman, 2009; Kulasegaram et al., 2017). Thus, building on prior knowledge and experience can enhance and improve learning, and learning is a constructive process (Kolb, 1984; Ausubel, 2012). Following the KELC (**Figure 2.1**) can enhance students' performance and understanding. Further analysis indicated that first-year medical students (**1MBBS-18/19**) found both the abdomen and the thorax difficult to interpret in cross-sectional images because of difficulties regarding image orientation and the students' lack of experience. The learning activities relating to cross-sectional-image interpretation (in the intervention and control groups) in the study for first-year medical students **(1MBBS-18/19)** (**Figure 5.7, 5.9**) covered only the thorax and the abdomen. Other topics such as the lower extremities were not addressed in this study for novice students.

The context-specific nature of education is important in considering learning challenges. The format of the curriculum, and the volume of information and complexity provided by instructors, determines the difficulty of the subject to some extent, and varies across educators, cohorts, and institutions. In this study, the information that medical students received was more detailed than the anatomical information given to the PAs, because of the differences in curricular content/learning outcomes/course requirements. This aspect was demonstrated by the results: the PAs did not find the abdomen and the thorax (**Figure 6.13**) difficult regions, whereas the first-year medical students (**1MBBS-18/19**) found both the abdomen and the thorax to be problematic (**Figure 6.20**). The PAs found the limbs to be challenging (**Figure 6.13**), because of the amount of information and detail introduced to the PAs regarding the limbs. The sample size of PAs may be a limitation in terms of the data collected from the PAs.

The volume of content to learn, teaching contact time, spatial abilities, and interpretation and understanding of the 3D aspects of the anatomical regions in 2D were all considered to be factors making anatomy learning challenging, which is in agreement with findings from earlier studies (Kramer and Soley, 2002; Hall et al., 2018; Lieu et al., 2018). All these factors should therefore be considered by educators in planning curricula. Additionally, all factors were pre-determined areas to be investigated through the questionnaire. These factors were confirmed in the focus group thematic analysis: students indicated that the volume of content was a factor making anatomy learning challenging (**Section 6.2.9**). Additionally, the first-year medical students' responses indicated that they would prefer more curricular time devoted to anatomy learning (**Figure 6.22**), and tasks (**Figure 6.32, Section 6.2.9**), and more resources (Sectra, 3DP models) (**Section 6.2.9, 6.3.7, 6.4.3**). However, this finding may prompt potential concerns regarding students becoming dependent on anatomy educators. This also conflicts with the aim of the new curricula in terms of decreasing the contact time and encouraging independent and self-directed learning.

Importantly, students must understand the basis of the major topics and concepts early in their anatomy learning and education to enable long-term learning of more complex topics. Introducing basic knowledge provides learners with an initial foundation to build upon when learning more complex topics, as proposed in constructivism (Kolb, 1984; Ausubel, 2012; Dennick, 2014). These theories suggest that students can cognitively create an understanding of what they are learning on the basis of their existing knowledge of the general anatomical structures and regions, thus connecting new knowledge and previous knowledge (Dennick, 2016)

7.1.2 Experienced students

Second-year medical students who had experienced all the anatomical science content in the Newcastle University MBBS programme perceived embryology to be significantly more challenging than other topics in the discipline to which they had been exposed during their medical studies (P < 0.001) (**Figure 6.1**). The same cohort found that histology, microanatomy, clinical imaging, and gross anatomy were all challenging.

Here, the second-year medical students found that embryology and histology were highly significantly (P < 0.001) more challenging than gross anatomy (**Figure 6.1**). This finding is not consistent with earlier work (Kramer and Soley, 2002) identifying gross anatomy as the major topic that students found difficult, followed by histology and embryology. This discrepancy may be explained by the prior study (Kramer and Soley, 2002) having been performed 20 years ago; anatomy education and teaching have since developed, and new curricula and resources have been introduced. Further analysis indicated that experienced students reported the head and neck, pelvis, and perineum to be more difficult than the limbs and the abdomen, which is in agreement with results from previous studies (Hall et al., 2018; Javaid et al., 2018) (**Figure 6.2**). Those studies (Hall et al., 2018; Javaid et al., 2018) have explained that the complexity of the head and neck, and neuroanatomy in general, as well as the difficulty in memorisation and visualisation of the terminology of the neuroanatomical structures, are the reasons why studying neuroanatomy is challenging.

These results confirmed that some topics that I had identified on the basis of our experience, such as the head and neck, were problematic for students. In contrast, students found the thorax to be the least challenging, possibly because the thorax is relatively less complex and has larger structures. It also integrated with clinical chest examinations to relate to clinical cases. Additionally, because the thorax is taught first, educators intentionally deliver content at a more basic level than that for subsequent regions. The brain, as an organ (**Figure 6.3**), and the nerves and plexuses (**Figure 6.5**), were the most difficult areas of study among experienced students, thus providing another indication that neuroanatomy is an area that most students find difficult. The fear of neuroscience and clinical neurology, known as neurophobia, was first described by Jozefowicz (Jozefowicz, 1994). The complexity of neuroanatomy leads to inadequate understanding, thus resulting in a fear and dislike of the topic among medical students and clinicians (Fantaneanu et al., 2014; McCarron et al., 2014; Pakpoor et al., 2014; Abushouk and Duc, 2016). A similar phenomenon applies to other complex concepts, such the fear of cross-sectional interpretation, called radiolophobia (Ben Awadh et al., 2022).

The lack of nervous system models and the difficulty in visualising the nervous system make learning neuroanatomy difficult (Lieu et al., 2018). As at Newcastle University, the vertebral column model featuring the spinal cord, spinal nerves, all vertebrae, and the vertebral artery; upper and lower limb models with peripheral nerves; cadaveric brains; and prosections showing key neurovascular structures are resources used to teach neuroanatomy. This is a key point indicating the importance of implementing 3D digital approaches for enhancing visualisation and understating of the nervous system. Concerns have been raised regarding a need for new methods and approaches to decrease neurophobia among students. Visuospatial skills are required to enhance the learning of neuroanatomy (Ridsdale et al., 2007). Introducing new resources such as computer-assisted learning can improve neuroanatomy education and decrease students' fear of neuroanatomy (Javaid et al., 2018). One way to remedy students' feelings regarding the difficulty of anatomy is introducing the anatomical structures and their clinical relevance and importance, and increasing the rate of repetition of the material taught (Bergman et al., 2013; Hall et al., 2018). Moreover, clinical imaging is relevant to clinical practice and provides an effective means of teaching cross-sectional anatomy (Al Qahtani and Abdelaziz, 2014).

One study (Harden, 1999) has reported that, according to students, repetitive studying of the subject and the materials, compared with assessment and teaching alone, increases knowledge retention and enhances motivation, as also informed by KELC (**Figure 2.1**). Moreover, more experienced students state that repetition is important to improve knowledge retention, and that repetition motivates them and increases opportunities for scaffolding and building on prior knowledge (Bergman et al., 2013), which is in alignment with constructivist theory (Ausubel, 2012; Dennick, 2014). Prior knowledge is essential for enhancing anatomy learning among medical students and can be achieved through preparation by reading or completing tutorials before class to aid in understanding of anatomical subjects. Iterative revisiting of topics, subjects, or themes throughout a course deepens understanding and learning, and ensuring clarity at each stage prevents information overload (Coelho and Moles, 2016). Thus, the digital and 3D resources (Sectra and 3DP models) used in this study should be used to enhance students' understanding.

The bones and ligaments were not considered to be challenging by students (**Figure 6.5**), probably because students were unlikely to experience difficulties in visualising these structures, given that the students had access to anatomical models in the DR anatomy laboratory or could palpate the bones in their bodies, including during clinical skills/clinical examinations. This possibility is supported by previous work indicating that access to skeletal models in the DR helps students visualise the skeletal system (Lieu et al., 2018). Physical models can enhance the visuospatial and 3D understanding of complex anatomical structures, thus allowing for better understanding (Lujan et al., 2013; Preece et al., 2013). Moreover, some second-year students in the focus group (**Section 6.1.8**) agreed that spatial awareness, which is defined herein as an understanding of 3D anatomical structures and relationships, is an important skill for understanding anatomy and forming conceptual connections between anatomical structures and systems.

The study results (**Figure 6.7**) indicated several topics and concepts making anatomy challenging, such as the volume of content, 3D spatial understanding, visualisation of the anatomical structures, and interpretation of anatomical features in 2D images. These items were pre-determined in the questionnaire on the basis of previous work (Hall et al., 2018; Javaid et al., 2018; Lieu et al., 2018). The volume of content was a factor making anatomy challenging for some second-year medical students, who stated in the focus group analysis (**Section 6.1.8**): "I think going back to do a revision is difficult." Students' perceptions regarding the difficulty of the volume of the materials or the anatomy course may be due to intrinsic factors, such as confidence and academic skills and abilities, or to factors related to the academic staff, such as the teaching methods, resources used, and curricula (Lieu et al., 2018). Unexpectedly, the second-year medical students did not find that decreased teaching contact time was a factor making anatomy difficult to learn **(Figure 6.7).**

In designing anatomy curricula, the volume of material and contact time should be considered to enhance anatomy learning for students, for example, by introducing effective short activities (e.g., Sectra and 3DP) and effective remote resources (e.g., SEP and HDBR). Students' responses indicated that they would prefer more resources (Sectra, 3DP models) (**Section 6.1.8**). Students are able to think independently when engaging with self-directed learning resources, and to choose their preferred learning goals and needs, such as reviewing the abdominal region during surgical rotation (Choi-Lundberg et al., 2016). Moreover, students should be encouraged to use self-directed learning resources to identify the most appropriate resources suiting their learning preferences, plan study strategies, and evaluate their leaning outcomes (Choi-Lundberg et al., 2016).

The students in the focus group discussion **(Section 6.1.8)** indicated that the 3DP models as a self-directed resource helped them study anatomy. Sectra was commonly considered a useful resource among the interviewees, particularly regarding clinical-imaging interpretation. The use of 3D printed models as a tool for learning anatomy was appreciated by students. Self-directed learning resources show promise regarding life-long learning in medicine (Murad and Varkey, 2008; Murad et al., 2010). Moreover, having appropriate resources such as models, and providing dissection sessions, can help students with visualisation and enhance their learning of challenging topics (Lujan et al., 2013; Haspel et al., 2014; Lombardi et al., 2014). The medical education and clinical skills needed to diagnose patients and provide accurate patient treatments are continually changing and developing; therefore, medical doctors require life-long learning and training (Marzo, 2018). Thus, students should be encouraged to depend on themselves, because in their professional careers, they must know how to find and understand new information in order to provide adequate and safe patient care (Marzo, 2018). One way to train medical students for life-long practice is developing their self-directed learning skills, which can help future doctors update their knowledge and skills (Ramamurthy et al., 2021).

7.2 Enhancing Cross-Sectional Image Interpretation with Multimodal 3D Approaches

In this study, significant improvements in image-interpretation performance in the same cohorts of learners were observed with the use of both multimodal 3D approaches (Sectra and 3DP models) and 2D cross-sectional images (**Figure 6.39, Figure 6.40**). These findings are likely to be due to multiple factors, including the value of active learning in which the students participate and engage in the learning activities (Freeman et al., 2014; Markant et al., 2016). Moreover, the tested students had limited knowledge and experience regarding the topics before the practical sessions (Ausubel, 2012).

Another reason for the students‘ enhanced performance might have been that both the control and intervention activities were designed to be based on small-group collaborative problem-solving, as underpinned by social learning theories (Piaget, 1970; Bandura and Walters, 1977; Vygotsky, 1980; Dennick, 2014). Students' interactions with fellow learners in small-group situations were likely to have supported their understanding of complex concepts through discussion, in which the expert student can help other students in understating the challenging topics faced during learning to promote scaffolding (Eagleton, 2015). This finding is supported by social constructivism theory, which proposes that the development of the mind and learning result from continual interactions within learners' social and academic environments (Vygotsky and Cole, 1978; Eagleton, 2015). Moreover, the zone of proximal development (Vygotsky and Cole, 1978) plays an important role in the scaffolding of the information that students obtain from more experienced people who help them in problem solving, thus advancing their knowledge and understanding (Vygotsky and Cole, 1978; Eagleton, 2015). Another study (Eagleton, 2015) has confirmed that assistance from experienced educators or colleagues supports students' understanding of physiology and anatomy. Thus, in the control and intervention learning activities in the study, which lasted 1 hour and 30 minutes and used a small-group format, students were encouraged to communicate with their peers and the demonstrator to understand difficult or unclear information, gain better understanding of clinical imaging, and improve their interpretation skills, given that learning is a shared social activity implemented in the classroom with interactive activities (Watson, 2001).

In comparing students' performance in the interpretation and understanding of anatomical structures and features in cross-sectional clinical-image activities, combined 3D approaches including both physical 3DP models and digital 3D resources (Sectra) were more effective ($P < 0.001$) in enhancing student interpretation performance than using only 2D cross-sectional static images (**Figure 6.41**).

In the current study, the first 3D anatomical structures and cross-sectional images to which first-year medical students (**1MBBS-18/19**) were exposed showed the anatomy of the cardiovascular system. Because of increases in cognitive load (Sweller, 1988; Van Merriënboer and Sweller, 2010) arising from limited and inadequate prior knowledge of basic anatomy (e.g., functions, structures, and terms) and the basic principles of interpreting clinical and cross-sectional images, novice students were expected to find the thorax a challenging topic, perhaps to a greater extent than the abdomen. These students were also expected to experience additional extraneous factors in studying the thorax, after having recently entered medical school. However, this was not the case (**Figure 6.20**). The Sectra and 3DP model learning activities effectively allowed students to overcome cognitive challenges while supporting image interpretation. Cognitive load theory was considered in designing the learning activity. Cognitive load theory was first developed by Sweller (1988) to describe models of human memory, which can be divided into sensory, working, and long-term memory (Young et al., 2014). Cognitive load theory focuses on three main cognitive architectures: memory system, learning processes, and different types of cognitive load (Young et al., 2014). The sensory memory receives information from the environment and stores it for several seconds (Khalil et al., 2005b). The working memory provides consciousness and processes auditory and visual information, but has limited capacity (Khalil et al., 2005b). Long-term memory stores the information permanently and has open capacity (Khalil et al., 2005b). Cognitive load comprises three types: intrinsic load (that associated with the main task), extraneous load (that not essential to the task), and germane load (the working memory that handles the intrinsic load that leads to learning) (Van Merriënboer and Sweller, 2010). The sum of these three loads equals the total cognitive load (Khalil et al., 2005b) and should not exceed the memory capacity to achieve effective learning (Khalil et al., 2005a). Therefore, cognitive load theory indicates that to achieve effective learning, the intrinsic load and germane load should be increased, and the extraneous load should be decreased, to allow the working memory to form schemata to be stored in the long-term memory (Young et al., 2014).

Furthermore, multimodal visualisation resources are likely to enable students to enhance the efficiency of visual information assimilation, thereby decreasing their cognitive load as they attempt to understand difficult anatomy topics (Khalil et al., 2005a). Students' cognitive load can be reduced through presenting task information and learning outcomes in small related segments to avoid overwhelming the working memory (Young et al., 2014). The learning activities in the study were divided into short activities to reduce the cognitive load (Khalil et al., 2005a) and enhance the working memory, as supported by experimental findings in which students had positive perceptions regarding the use of Sectra and the 3D model resources (**Figure 6.31, Figure 6.33**).

The students' highly significant improvement ($P < 0.001$) in interpreting the cross-sectional clinical images of the thorax, compared with the abdomen (**Figure 6.41**), suggested that the use of multimodal resources (Sectra and 3DP models) enhanced students' performance and helped them overcome the challenges in studying the thorax.

The success of the interpretation of cross-sectional thorax images was probably due to the use of a combination of Sectra and the 3DP models, which allowed for 2D–3D transition (Keenan and Powell, 2020), as supported by both the modality preferences for learning hypothesis (Lodge et al., 2016) and previous work demonstrating the value of multimodal learning (Preece et al., 2013; Wainman et al., 2018; Ben Awadh et al., 2022). The modality appropriateness hypothesis is described as 'using the right tools for the right job'. For example, because anatomy is in 3D, using 3D resources rather than, e.g., only 2D images (as in the control in the experimental study), is appropriate to study anatomy; specifically, to enhance understanding of the 3D aspects of anatomical structures. Therefore, interpretation of 2D cross-sectional images is recommended to be combined with 3D resources (Sectra and 3DP models).

The present findings (**Figure 6.31, Figure 6.33**) appear to be consistent with other research indicating that students have positive perceptions of learning activities that supplement multimodal approaches, including both 2D images and 3DP models (Fasel et al., 2016). Providing a range of learning resources, including Sectra as digital resource and 3DP models as physical resources, in practical sessions and during thorax interpretation activities, strengthened this study, and supported the hypothesis that these resources facilitate anatomy learning and understanding by providing different viewpoints of anatomy observation (Ward and Walker, 2008b; Eagleton, 2015; Ben Awadh et al., 2022). A combination of multimodal resources and approaches involving both visual and haptic observation has been indicated to improve and enhance learning (Woods and Newell, 2004; Jones et al., 2006; Minogue and Jones, 2006; Shapiro et al., 2020). Multimodal resources and approaches have been implemented successfully and effectively in anatomy education and learning (Sugand et al., 2010; Naug et al., 2011; Estai and Bunt, 2016; Ben Awadh et al., 2022). Therefore, in the future, encouraging more use of 3DP models together with Sectra may promote cognitive multi-sensory learning experiences. Additionally, the use of 3DP can decrease stress and anxiety among students who avoid contact with cadaveric material (Lim et al., 2016). Applying a multimodal approach helps students appreciate the 3D aspects of anatomy. The use of Sectra and 3DP models as multimodal and sensory inputs in our study could be argued to have increased students' cognitive load (Van Nuland and Rogers, 2016b). However, a previous study has indicated that combining visual-technology-enhanced learning resources actually decreases cognitive load in students during anatomy learning (Küçük et al., 2016).

Although an increase in task time in cross-sectional learning activities has been recommended in previous studies (Fasel et al., 2005; Gibbs, 2010) as well as by the cohort, who suggested increasing the time spent using Sectra and the 3DP models (**Figure 6.32**), the participating students showed significantly improved interpretation abilities between the pre-test and the post-test for both activities using Sectra with 3DP models (**Figure 6.39**) and 2D images (**Figure 6.40**), thus suggesting that the 10 minute activity was satisfactory. The reasons underlying the positive value of short activity times can be explained by students' preference to be engaged for short times, thus decreasing cognitive load and enhancing students' understanding. However, that finding may conflict with the notion that spending more time on a task helps students learn the material better.

Combined multimodal 3D approaches can enhance image interpretation, and these resources were found to improve knowledge gain (**Figure 6.39, Figure 6.41**). Thus, anatomy educators in the future should be encouraged to implement similar resources and approaches to support traditional teaching methods. Additionally, the use of 2D digital representations of human anatomy can result in poorer knowledge retention than the use of physical 3D models (Preece et al., 2013; Wainman et al., 2018), whereas the use of Sectra to provide students with 2D clinical images and 3D digital representations of anatomical structures has been shown here to increase knowledge retention (Ben Awadh et al., 2022). Moreover, identifying the challenging topics and areas in anatomy learning can lead to changes in how these areas are taught (Hall et al., 2018), including the introduction of digital and 3D resources to effectively supplement traditional anatomy learning approaches (Keenan and ben Awadh, 2019a).

7.3 The importance of 2D-3D Transition in Cross-sectional Image Interpretation

Clinical-image interpretation appeared to be a problematic area for medical students, regardless of their experience level (**Figures 6.1, 6.12, 6.19**). Further investigations performed to identify the reasons making clinical-image interpretation challenging indicated that students from different cohorts with different experiences perceived that 2D–3D transition is a factor making anatomy and clinical image interpretation challenging (**Figures 6.7, 6.17, 6.22**); therefore, reciprocal 2D–3D transition (Keenan and Powell, 2020) is important to enhance students' clinical-image interpretation. Reciprocal 2D–3D transition has been proposed to be a reciprocal cognitive transition in which 2D visual information is used to understand 3D structure; in contrast, objects in 3D are used to reconcile prior understanding of 2D images (Keenan and Powell, 2020).

Therefore, in the context of clinical-image interpretation, a fundamental appreciation of 2D–3D transition is necessary to understand that 2D cross-sectional images are deconstructed from 3D anatomy. CT and MRI scans typically present anatomical structures in a sequence of parallel slices as 2D cross-sectional images, usually in the sagittal, coronal, or axial planes. Plain radiographs are also presented as 2D images from a particular point of view depending on the region or structure under investigation. The identification of 3D anatomical structures in 2D clinical images is therefore a primary learning process required for the interpretation of clinical images (Keenan and Powell, 2020). Clinical-image interpretation is likely to require mental visualisation of anatomical regions and processes cognitively associated with prior knowledge of the 3D representation of anatomical structures. The use of the 3D rendering function in Sectra and the use of 3DP models may therefore be more valuable in clinical-image interpretation than using only 2D clinical images, in which no reciprocal 2D–3D transition is required. These findings were supported by the questionnaire data from the PA students (**Figures 6.28, 6.29**) and first-year medical students (**Figures 6.31, 6.33**), and by the significant improvement in students' performance in interpreting clinical images (**Figure 6.39, 6.40, 6.41**).

According to constructivist theories (Ausubel, 2012; Dennick, 2014, 2016), cross-sectional interpretation starts with simple steps to create experiences and knowledge, such as becoming familiar with the orientation of the patient (prone, supine) and the clinical image planes, and the density and colour of the structures on clinical images, such as black regions indicating air. In the next step, more complicated information is introduced so that students can build and develop on their prior knowledge, such as understanding the locations of anatomical structures and regions and their relationships with surrounding features. The process of learning more complex material by building on prior knowledge can be described by constructivist theory, which states that learning is the act through which new knowledge connects with and builds upon pre-existing knowledge (Vygotsky and Cole, 1978; Kolb, 1984; Ausubel, 2012; Dennick, 2014, 2016). Moreover, Kolb has proposed that "learning is the process whereby knowledge is created through the transformation of experience" (Kolb, 1984); i.e., learners rely on their experience during learning. Thus, anatomy educators must build student experience in clinical-image interpretation to improve their ability to effectively transition between 2D and 3D understandings.

Spatial ability comprises several other elements in addition to MR. Matching of the representation of an object image with a representation in long-term memory is a process called object recognition (Hummel, 2000). Object recognition is likely to be important for the brain to understand the structures in clinical images. Several theories explaining how the brain uses 2D images to reconstruct 3D representations for object recognition can be described by two approaches: view-based and structure-based approaches (Wu et al., 2012).

According to the view-based (image-based) approach, a collection of stored 2D views of retinal images in the brain can be reconstructed into 3D images based on different views of the 2D images (Lawson et al., 1994; Tarr and Bülthoff, 1998). In the view-based approach, no 3D models are viewed for recognition, and therefore MR is not required; recognition of the object is accomplished by connection between numbers of stored views (Riesenhuber and Poggio, 2000). For example, the kidney can be presented and rotated 360 degrees, so that all sides can be visibly observed, thus allowing students to mentally construct a 3D representation of the kidney, which then can be mentally rotated. Consequently, when students see a 2D image of the kidney, they can refer to the mentally constructed 3D representation of the kidney.

The structure-based approach proposes that object recognition by the brain occurs in a series of steps and stages that are presented as a collection of 3D volumes that are remapped into a 3D-object-centred representation (Marr and Nishihara, 1978; Marr, 1982). In Marr's computational frameworks (viewpoint invariant), the viewing angle or side of an object does not affect the observer's ability to recognise the object (Marr, 1982). For example, the liver can be identified if it is viewed from the top or the sides. Consequently, understanding these models is important in designing approaches to enhance 2D–3D transition for students to improve their clinical-image interpretation.

For anatomy learning and clinical-image interpretation, the view-based approach has been proposed as an effective model of 2D–3D transition in using 2D cross-sectional images, as supported by previous studies, in which students mentally created a 3D representation of anatomical structures from observation of 2D cross-sectional images (Garg et al., 2001; Wu et al., 2012). Students therefore must be exposed to more 2D clinical images to be able to reconstruct 3D representations of the viewed object (Keenan and Powell, 2020). Here, students were encouraged to access cross-sectional images through Sectra and SEP to enhance 2D–3D transition and allow for better understanding of the 3D representation of the anatomical structures presented in the 2D cross-sectional images. Additionally, students were encouraged to use the 3D rendering function in Sectra to create a 3D digital model of the 2D clinical images of the heart and to use 3DP models of the heart to emphasise the transition between 2D and 3D representations. Together, the findings presented here (**Figure 6.39**) indicated that learners may be able to interpret clinical images by constructing a mental 3D model of 2D cross-sections while being supported in rapid and reciprocal 2D–3D transitions through the simultaneous use of a combination of 2D clinical images, 3D printed models, and 3D digital models. Thus, the implementation of combined multimodal 2D and 3D learning resources in learning activities is likely to enhance visualisation, identification, interpretation, and understanding of anatomical structures in cross-sectional clinical images.

7.4 Cross-sectional Anatomy Learning May be Independent of Spatial Ability

Previous studies have demonstrated positive relationships between MR ability and knowledge of anatomy (Guillot et al., 2007; Hoyek et al., 2009; Fernandez et al., 2011; Lufler et al., 2012; Nguyen et al., 2014; Sweeney et al., 2014). Spatial ability is likely to be an important skill for students studying human anatomy in cognitively manipulating viscera and other structures to visualise their anatomical relationships, and may support the study of anatomy in different sectional planes (Jang et al., 2017).

The questionnaire data presented herein indicated that students from different cohorts with different experiences perceived that spatial ability is an important skill for anatomy learning and clinical-imaging interpretation (**Figures 6.8, 6.18, 6.24**). However, despite a broad variation in MR test scores (**Figure 6.42**), a very weak positive correlation ($R^2 = 0.053$) was found between learning performance with the use of Sectra and 3DP models and MR, thus indicating that MR ability appears to be weakly correlated with anatomy learning, as supported by a previous study (Sweeney et al., 2014). Moreover, regression analysis also indicated a very weak negative correlation ($R^2 = 0.001$) between the MR test scores of the participants and their performance scores with the use of 2D images for clinical interpretation. Together, these findings suggest that clinical-image interpretation is independent of MR ability. Nonetheless, these findings appear counter intuitive, with several previous studies having reported that anatomy learning and clinical-imaging interpretation is positively influenced by students' MR abilities (Guillot et al., 2007; Hoyek et al., 2009), because the students' performance were improved more for the students with high MR abilities.

Although previous work has demonstrated that MR training, in which students rotate a model of the carpal bones for nine minutes in different views, can enhance students' performance in answering anatomy questions requiring spatial ability, such as practical tests or spotters (Garg et al., 2001). The findings presented herein (**Figures 6.39, 6.50, 6.51**) revealed highly significant improvement ($P < 0.001$) without a need for formal MR training, regardless of students' spatial ability skill level. Interpreting anatomical features in clinical images may require spatial abilities other than MR. However, Sectra + 3DP model and 2D image activities might themselves have been a form of MR training, in that students' spatial ability can be enhanced during anatomy learning (Lufler et al., 2012; Vorstenbosch et al., 2013), and that computer-based and 3D visualisation resources can improve students spatial abilities in studying anatomy (Fernandez et al., 2011) and clinical imaging (Vuchkova et al., 2011).

Presentation formats and digital technology resources can be effective teaching pedagogies to support spatial ability improvement among students (Nguyen et al., 2012; Berney et al., 2015), particularly those with relatively weak spatial abilities (Berney et al., 2015). Students with weaker spatial abilities and skills have been found to be able to use visualisation resources to build an effective mental representation of anatomical structures, such as the scapula, thus enhancing their performance in identification tasks (Berney et al., 2015).

Some studies have suggested that by using appropriate multimodal 3D software and drawing diagrams, students' spatial abilities can be improved (Newcombe, 2010). Additionally, 3D digital resources and 3DP models are effective teaching resources that can improve anatomy learning, regardless of students' MR abilities (Jamil et al., 2019). The MR trained intervention group and an untrained control group both showed significant improvements ($P < 0.05$) in their knowledge-gain test scores compared with their pre-test scores, thus indicating that teaching using 3D resources can enable performance gain independently of MR training and MR abilities (Jamil et al., 2019). Therefore, the implementation of 3D multimodal resources may provide educational value in the existing pedagogies for teaching anatomy by enhancing the performance of students with a range of MR and spatial abilities, with or without prior MR training (Ruisoto Palomera et al., 2014; Jamil et al., 2019), which is in agreement with the findings presented herein (**Figure 6.39, 6.50, 6.51**). There is no time available for spatial ability training in anatomy curricula, given the large decrease in contact time. However, the study findings indicated that students can perform well without spatial ability training. Importantly, however, 3D visualisation resources that present material in multiple orientations and layers may increase cognitive load, particularly for individuals with relatively weak spatial abilities; consequently, students with relatively weak spatial abilities may be unable to accurately mentally rotate different anatomical structures (Huk, 2006), thereby affecting their memorisation and understanding.

7.4.1 Spatial ability in clinical practice

Spatial ability is likely to be an important skill for medical students, not only for anatomy learning and clinical interpretation, but also for their future professional careers in clinical practice. Medical students will rely on their mental and spatial abilities in their medical profession while performing clinical diagnosis, medical procedures, and surgery, because the internal body structures are not visible (Wanzel et al., 2002; Hedman et al., 2006; Petersson et al., 2009; Abe et al., 2018). Robotic techniques are now widely used in surgery, including thoracic surgery, as well as urology, which requires an ability to identify the position, size, and location of anatomical structures by mentally manipulating objects (Abe et al., 2018). For example, students with higher MR skills performed better with fewer repeats in a robotic suturing task in which the students must mentally determine the orientation of the needle for manipulation (Abe et al., 2018). Abe has also claimed that students with low mental scores can achieve scores comparable to those of the highest performing students after only three suturing sessions (Abe et al., 2018). Additionally, as described above, spatial abilities and MR are likely to be important for the understanding and interpretation of clinical images, such as MRI and CT scans, which are 2D slices of 3D anatomical structures (Vuchkova et al., 2011; Keenan and Powell, 2020).

Finally, students' pre-existing visual-spatial ability levels may indicate their performance in gross anatomy assessments. Further analysis has shown that the learning of gross anatomy can improve students' long-term spatial abilities (Lufler et al., 2012; Vorstenbosch et al., 2013). The results of the MR tests presented here (**Figure 6.42**) may suggest that the learning activity design and delivery of Sectra and the 3DP models with 2D clinical images as multimodal learning activities might have allowed students to overcome any inherently limited spatial skills.

7.5 Positive Perceptions of Students Toward 3DP models, and Digital and Remote Learning Resources

The total teaching time for anatomy learning in medical curricula is an important factor in enhancing students' anatomy learning, because more time spent on a subject, including anatomy (Bergman et al., 2008), increases knowledge and consequently is likely to contribute to successful assessment performance. Additionally, more time available allows more topics and concepts of anatomy to be taught; consequently, students prefer longer anatomy teaching times (Sugand et al., 2010). However, the introduction of new curricula in some universities has markedly decreased teaching times, because medical curricula have been redesigned to focus on clinically relevant disciplines such as pharmacology, microbiology, and immunology (Aziz et al., 2002), and approaches stressing clinical relevance (Smith et al., 2016b). At Newcastle and elsewhere, reductions in teaching time have been implemented for anatomy, embryology, and clinical imaging (Aziz et al., 2002; McKeown et al., 2003; Drake et al., 2009). Thus, anatomy educators must increase the opportunities for face-to-face teaching by improving efficient and effective learning activities. Unfortunately, at Newcastle University, face-to-face teaching was decreased because of the introduction of new curricula. As of March 2020, COVID-19 was considered a high-risk infectious disease in the UK. The WHO declared COVID-19 a pandemic, and most countries including the UK took actions to protect communities and avoid the spread of the disease. Newcastle University followed the government's advice by announcing new measures designed to reduce coronavirus spread (Longhurst et al., 2020). On the 17th of March 2020, the University stopped all face-to-face classes and suspended all non-essential work in all its research environments, thus resulting in a need to rapidly transition to remote learning as an alternative. The COVID-19 pandemic resulted in the development of remote learning resources and environments, which were required to effectively deliver teaching (Evans et al., 2020). In anatomy education, supplementing anatomy dissection practical sessions with effective self-directed learning resources has become important (Evans et al., 2020; Longhurst et al., 2020; Iwanaga et al., 2021).

Implementing technology-enhanced learning approaches with traditional teaching methods has been shown to be effective anatomy teaching and learning (Elizondo-Omaña et al., 2004; Pereira et al., 2007; Green and Whitburn, 2016), health profession education (Liu et al., 2016), and radiology for anatomy (Shaffer and Small, 2004; Webb and Choi, 2014).

However, research investigating the value of technology-enhanced learning approaches has not always provided comprehensive evidence of their benefits in anatomy education in terms of improvements in learning (Clunie et al., 2018).

The second-year medical students (2MBBS-17/18) in the study perceived that Sectra and 3DP models (**Figure 6.9**) were valuable resources that supported their anatomy learning.

Additionally, the same cohort suggested that they needed more online interactive self-directed learning resources to enhance their anatomy education **(Figure 6.10)** by enabling them to view anatomy in 3D and to develop a better understanding of how structures might appear in the body. Additionally, self-directed learning resources provided flexibility to students, because they were able to access these resources at any time or place.

Further studies were performed to gather more insights from different cohorts to identify their perceptions regarding the most useful digital and 3D anatomy learning resources. Both the PA students and first-year medical students had positive perceptions regarding the use of both Sectra and 3DP models to enhance their anatomy education (**Figures 6.28, 6.29, 6.31, 6.33**). Students reported that Sectra enhanced their 3D understanding of the anatomical structures and improved their gross anatomy understanding and interpretation of cross-sectional images (**Figures 6.28, 6.31**). These results are consistent with those from a prior study (Petersson et al., 2009), in which students expressed positive perceptions toward the use of 3D interactive resources. Another study has shown that the integration of virtual dissection is a valuable resource for learning anatomy and radiology, because students indicated that the virtual resources improved their understanding of clinically relevant anatomy, pathology, and diseases (Darras et al., 2020)

Furthermore, students perceived that 3DP models provided added value in their anatomy learning by supporting their 3D understanding of anatomical structures, increasing their confidence in identifying and locating anatomical structures, and providing useful self-directed learning resources outside the DR **(Figures 6.29, 6.33).** Similar findings have been found in a study (Backhouse et al., 2019) in which the participating students preferred 3DP models of the skull in learning orbital bone anatomy to improve their understanding and visualisation of the relationships between bones. In another study (Smith et al., 2017), medical students valued the use of 3DP as a self-directed learning resource that students could use off-campus. Moreover, students' interest in congenital heart diseases can be stimulated by introducing 3DP models to increase engagement in learning activities (Su et al., 2018).

However, all participating students from different cohorts agreed on the need for remote interactive resources to improve their anatomy learning experiences (**Figures 6.10, 6.30, 6.35**). Because modern digital and online resources and 3D approaches are becoming more widely implemented (Sugand et al., 2010; Chapman et al., 2013; Hackett and Proctor, 2016; Smith et al., 2017) and used to enhance anatomy education and to focus on the anatomical topics and concepts that students find most challenging (Turney, 2007), SEP was chosen in this study to provide students with an interactive online resource. SEP was chosen because the anatomy department in the medical school (Newcastle University) where the study occurred already had user subscriptions for the students. Additional financial, logistical, and educational factors were considered in choosing SEP to accelerate the study process.

SEP (Keenan and ben Awadh, 2019a; Sectra, 2021b) was implemented as a self-directed learning resource. The data from the focus group showed that students had positive perceptions of the real clinical cases, which enabled understanding of the locations of, and relationships between, anatomical structures (**Figure 6.44**, **Section 6.3.7**). SEP can be integrated within traditional teaching methods or for remote teaching purposes. SEP can serve as a remote resource to help students learning anatomy, clinical-image interpretation, radiology, and embryology.

Our findings suggest that SEP is an effective remote resource to enhance students' learning of anatomy, which is in agreement with findings from previous studies (Choudhury et al., 2010; Van Nuland and Rogers, 2016b; Van Nuland and Rogers, 2016a; Backhouse et al., 2017). However, some of our results were inconsistent with those of a previous study (Pickering and Swinnerton, 2019) that reported no association between the use and the implementation of technology-enhanced learning resources and student outcomes. In contrast, our study showed that the use of digital technology resources greatly affected students' understanding and improved their performance (**Figure 6.51**). Additionally, students appreciated the use of 3D printed models as a tool for learning anatomy **(Figures 6.9, 6.29, 6.33),** although the focus group findings **(Section 6.1.8)** did not identify the specific underlying reasons. Previous work has demonstrated that having a sufficient number of 3DP models outside the DR can provide a useful remote self-directed learning resource for students (AbouHashem et al., 2015; Smith et al., 2017; Keenan and ben Awadh, 2019a) to support and enhance remote multimodal learning. The use of digital and remote learning resources to supplement traditional resources not only provides educational experience for students but also helps them develop life-long learning strategies as medical information continually develops (Sugand et al., 2010; Marzo, 2018; Ramamurthy et al., 2021).

The work presented here is informed by the technology-enhanced learning evaluation model (TELEM), which describes four levels (0–3) of TEL evaluation studies (Pickering and Joynes, 2016; Clunie et al., 2018). The four levels are defined as; level 0, preliminary evaluation in which an evaluation of need and model evaluation should be performed to ensure the need for the TEL resource; level 1, divided into learning stratification and learner gain; level 2, learner impact; and level 3, institutional concerns, financial benefits, and impact (Pickering and Joynes, 2016; Clunie et al., 2018). The preliminary evaluation (level 0) was based on the personal experiences of anatomy educators with respect to the need to implement teaching resources to compensate for decreased contact time. The types of resources (Sectra and 3DP models) had been planned, discussed, and implemented by educators to optimise benefits for students and to align with the desired learning outcomes.

Level 1 is divided into two main areas: 1) student satisfaction and 2) student gain (Pickering and Joynes, 2016). Student satisfaction (level 1), as previously described (Pickering and Joynes, 2016; Clunie et al., 2018), can be measured with a Likert-type scale questionnaire and focus group, as conducted in our study. The questionnaire results **(Figures 6.31, 6.33, 6.44, 6.53)** and focus group responses **(Sections 6.2.9, 6.3.7)** indicated that students had positive perceptions regarding Sectra VT, 3DP models, SEP, and HDBR/interactive PDF digital embryology resources. Learner performance was measured in pre- and post-test experimental studies (**Figures 6.39, 6.50, 6.51**) to identify student knowledge gains with the implementation of new resources, as recommended by TELEM (Pickering and Joynes, 2016; Clunie et al., 2018). Furthermore, the findings herein **(Figure 6.41)** indicated that the improvements in student clinical interpretation performance with the combined use of Sectra and 3DP models, compared with 2D images as a control, were highly significant ($P < 0.001$). Learner impact (level 2) is a complex step in the TELEM model (Pickering and Joynes, 2016; Clunie et al., 2018), in which detailed information on student use is investigated. Level 2 requires the identification of relationships between resource impact and student assessment outcomes. Unfortunately, level 2 could not be directly addressed in the work presented herein because of participant attrition and limitations in student recruitment (**Section 8.1**). Additionally, tracking of individual students' use, frequency of access, or duration of use was not logistically or ethically possible. The link between individual student image-interpretation performance and summative assessment results was not explored due to the potential for generating invalid data due to contamination from student usage of other learning resources in the 3–6-month period between intervention and assessments. The low number of summative assessment questions relating to cardiovascular imaging, or even imaging and anatomy in general, would also not have provided sufficiently valid data if this approach had been implemented. Assessments of all discipline strands in medicine are combined within integrated assessments at Newcastle University, with no single anatomy exam. The number of anatomy items in assessments therefore comprises a small proportion of the total questions. Moreover, access to assessment data for research purposes is not always possible due to institutional regulations.

Level 3 of the TELEM refers to the financial impact of the resources used. Level 3 assessment was not conducted because the full cost feasibility and the benefits of the resources used was beyond the scope of this project. However, a brief cost-effective plan has been designed for procurement of digital 3D resources, and the cost per learner studying anatomy across several degree programmes within FMS at NU during the project period (n = ~1000) can be calculated. Comparisons in costs with alternative resources can also be made. For example, the Raise Pro2 3D printer, was costed at approximately £3000 at the time of purchase (spring 2018), equivalent to a cost of £3 per FMS anatomy student, and equivalent to the cost of six commercial heart models, at £549.00 per unit (Adam, Rouilly Company). Moreover, a 3D printer has the potential to print as many models as may be required in specific learning situations (ideally one model for each student). The cost of 3DP models varied from £0.46 to £3.50, depending on the complexity and size of the model. Additionally, institutional student SEP licences were costed at £4000 per year. Level 3 can be assessed in future work, in which a full feasibility study could be performed to determine the cost benefits and the cost effectiveness of the resources.

Importantly, a previous study has found no relationship between student engagement and use of technology-enhanced learning resources with their assessment performance (Pickering and Swinnerton, 2018). The authors described how an understanding of engagement as emotional, behavioural, or cognitive is important for the design and implementation of new teaching resources. A particularly notable point with respect to new technologies used in TEL is that emotional engagement and enjoyment of resources does not necessarily lead to deep and effective learning and understanding of anatomical concepts (Clunie et al., 2018; Keenan and ben Awadh, 2019a; Pickering and Swinnerton, 2019). Moreover, the resources that students enjoy most may be used more frequently, thereby increasing student engagement (Pickering and Swinnerton, 2019). Thus, combined behavioural, cognitive, and emotional engagement in using the TEL resources may result in effective learning (Pickering and Swinnerton, 2019). The type and extent of student engagement should therefore be considered when implementing new digital and 3D resources in anatomy learning and when analysing positive perceptions regarding use of the resources (**Figures 6.31, 6.33, 6.44, 6.53**).

7.6 Novice Students Value Digital Approaches to Enhance Embryology Learning

Embryology is an important part of the medical curriculum, because this subject provides an important basis for the understanding and management of antenatal care and many clinical conditions, such as infertility, ectopic pregnancy, and congenital birth defects (Hamilton and Carachi, 2014; Abdel Meguid et al., 2022). Indeed, students have noted that cardiac embryology is important for clinical practice (Holland and Pawlikowska, 2019) owing to the prevalence of common cardiovascular abnormalities. Despite appreciating the clinical relevance of the discipline, medical students typically find studying embryology to be particularly demanding (Kazzazi and Bartlett, 2017). Those findings are consistent with the results described herein, in which second-year medical students considered embryology to be the most challenging topic ($P < 0.001$) to which they had been exposed during their medical programme, among all the options provided (**Figure 6.1**). Despite the importance of embryology in the education of medical students, institutions in America, Australia, and the UK (including Newcastle University) have recently decreased the total time devoted to teaching anatomical sciences; consequently, embryology education has nearly disappeared from some anatomy courses (Hamilton and Carachi, 2014; Ben Awadh et al., 2022). Additionally, in a study conducted at the University of Glasgow, most (81%) participating medical students agreed that embryology should be part of the medical curriculum, because it is a difficult topic to learn and apply to real clinical cases (Hamilton and Carachi, 2014).

It is important to note that most embryology education studies have been based on student perceptions rather than on experimental studies of student performance. Moreover, student preferences regarding traditional teaching methods versus modern learning resources for embryology have not been established (Hamilton and Carachi, 2014).

Nonetheless, student perceptions can be informative when investigating the value of embryology learning resources. For example, and in support of data presented herein **(Figures 6.53),** the use of virtual 3D models and animations has been identified as supporting students understanding and visualisation of detailed embryonic structures and their development (Patel et al., 2018). Another study (Holland and Pawlikowska, 2019) reported that videos and animations aid in students' learning of embryological concepts, with resources being appreciated by 46% of students. Moreover, the use of web-based multimedia, including 3D graphics and 3D models for manipulation, and 2D animation and 2D cross-section resources, are welcomed by students and are likely to support long-term knowledge retention and comprehensive skills (Marsh et al., 2008). Consequently, to enhance embryology education for Newcastle University medical students, remote digital embryology resources were introduced. Coincidentally, this implementation occurred alongside the cancellation of on-campus teaching during the early weeks of the COVID-19 pandemic, which further limited the opportunities for synchronous in-person delivery of embryology content. The specific digital embryology resources used herein were the HDBR 3D Atlas (Kerwin et al., 2010; Abdel Meguid et al., 2022) and Sectra interactive 3D PDFs (de Bakker et al., 2012) (**Section 5.8.1**). These digital embryology resources were embedded within the MLE platform to enable remote asynchronous delivery of self-directed learning resources and activities involving student interactions with multimodal resources. Before implementation of the embryology digital resources in the study, students had been using 2D lectures, 2D textbooks, and YouTube videos to study embryology (Abdel Meguid et al., 2022). The students perceived benefits in the implementation of the digital embryology resources, in terms of enhancement in their embryology learning and understanding (**Figure 6.53**). More specifically, the students reported that their understanding of the 3D nature of the embryology of the heart was improved by integration of the 3D digital resources (**Figure 6.53**). These findings were consistent with those in previous studies (Moraes and Pereira, 2010; Holland and Pawlikowska, 2019).

The HDBR digital heart models were likely to be valuable for student visualisation of the development of the heart through different CSs, because the content was presented in a dynamic 3D format that may promote deeper learning (Holland and Pawlikowska, 2019). Understanding of spatial relationships might also have been improved through engagement with the HDBR 3D Atlas, which enables navigation through, and alteration of the viewing angles of, 3D models of the embryo and embryonic structures (**Figure 6.54**). Moreover, providing images and animations of real embryos is a major advantage of the HDBR Atlas. The ideal embryology resource would likely be an interactive resource presenting development in 3D, dynamically from fertilisation to the foetal stage, and would be based on imaging of real human embryos/foetuses. Students found that visualisation of the embryonic structures at different stages was useful, thus helping them visualise and understand the development of the heart through the different stages (**Section 6.4.2, Figure 6.54**). The 3D aspect of the HDBR Atlas helped the students understand the 3D representation of the embryo, whereas 2D resources can be misleading (**Section 6.4.2, Figure 6.54**). The questionnaire data **(Figure 6.54)** revealed several drawbacks of the HDBR Atlas: some students found using the HDBR digital heart models to be difficult and overwhelming, and they recommended provision of more labelled models and providing more details in the tutorial guide. Additionally, the Sectra interactive PDF documents are likely to have supported visualisation of the heart in relation to the development of the other embryonic systems, while providing labels for the different structures (**Figure 6.55**). The interactive PDFs gave students the option of isolating any structure from the heart to appreciate their sizes and positions in relation to other systems in the embryo (**Section 6.4.2, Figure 6.55**). Moreover, the students found the labelling and the colours in the interactive PDFs to be useful, because they were easy to refer to and aided in connecting the different structures (**Section 6.4.2, Figure 6.55**). Some students had technical difficulties in using the interactive PDFs and indicated that they required more detailed guidance (**Figure 6.55**). Previous studies have suggested that embryology learning resources should be short, meaningful, and aligned with the curriculum to avoid overloading students with extraneous content (Holland and Pawlikowska, 2019). This concept was applied herein to the design of HDBR and interactive PDF learning activities to decrease cognitive load (Abdel Meguid et al., 2022). The focus group thematic analysis showed that the digital embryology resources, as self-directed learning resources that can be accessed at any time, provided the students with flexibility and increased their engagement (Pickering, 2015), because they were able to use the resources on their own time anywhere (**Section 6.4.3**). In this study, the students provided recommendations to improve the use of embryology digital resources, such as the provision of more guidance, more labels, and easier access to the resources (**Figure 6.57, Section 6.4.3**).

7.7 3D Spatial Observation and Understanding is a Threshold Concept

The novice medical students in this study identified clinical-imaging interpretation to be a challenging topic in learning anatomy (**Figure 6.19**), thus indicating that this ability may be a threshold concept. A threshold concept is defined by (Meyer and Land, 2003) as "akin to a portal, opening up a new and previously inaccessible way of thinking about something." Students should view and understand the concept before progressing in their understanding of the viewed subject (Hill, 2012). Additionally, a threshold concept is a troublesome aspect of understanding a specific knowledge or idea within a subject (Meyer and Land, 2003; Land et al., 2005; Meyer and Land, 2005; Meyer et al., 2010). Thus, knowing why certain areas or topics are more troublesome to students than others, and how these difficulties can be minimised, is important (Land et al., 2005). The threshold concept provides a way of interpreting, understanding, or viewing a subject that can emerge from transformed information, either from an internal view of a subject or a worldview (Meyer and Land, 2005). Additionally, the threshold concept has three main characteristics—transformative, irreversible, and integrative—that must be situated within the wider discipline, such that the understanding of the concept gives students new insight into the discipline as a whole. Threshold transfer requires the integration of new concepts with prior knowledge and understanding; during the transfer of the threshold, some fluctuation in understanding can occur before full transformation and understanding (Land et al., 2005; Meyer and Land, 2005; Meyer et al., 2010; Hill, 2012). After students use the threshold concept, they become more confident and able to combine different aspects of a subject in their analysis of problems (Land et al., 2005). Clinical-imaging interpretation itself might be argued not to be a threshold concept. However, clinical-imaging interpretation learning activities can facilitate overall understanding of anatomy as a discipline (Keenan, 2016). Additionally, 3D spatial observation and understanding are likely to be a threshold concept, which therefore also encompasses embryology learning. Moreover, clinical image interpretation requires abilities such as 2D–3D understanding that are applicable to a broader understanding of the anatomy discipline, and this skill can be a threshold concept. Additional abilities such as visitation, observation and reflection upon anatomical structures and their features, and understanding of the 3D aspects of the human anatomy and embryology, may be associated with threshold concepts that could be developed and improved during clinical image interpretation activities and embryology learning. Moreover, clinical examination requires critical observation (Frere et al., 2017), and this skill can be a threshold concept for medical students because it extends to broad areas of medicine beyond anatomy. Students' awareness of anatomical variation between individuals in relation to anatomy understanding in clinical practice and diagnosis can be considered a threshold concept. Enhancing students' awareness of the discussed areas may support findings indicating that learning clinical image interpretation enhances anatomy learning because it may support the development of 3D spatial skills.

Chapter 8. Limitations

8.1 General Limitations

The main weakness of this study was the limited availability of students (sample size) in some portions of the study. Additionally, some students did not complete all portions of the study, thus resulting in missing data. The gatekeepers' regulations required participation in the study to be optional, and the limitations in advertising the study might have resulted in a low participation rate in some portions of the study. The low participation was considered in subsequent years to ensure high responses from students to strengthen our findings.

In the case of the PAs, the sample size was small, which is a weakness of the study. However, this study was used as a pilot to validate the questionnaire data. The limited time given to students to perform some portions of the study was a major limitation, e.g., 10 minutes for the use of Sectra and 3DP. Furthermore, MR measures only one element of spatial ability, and this aspect is another potential limitation of the study. Additionally, the MR test measures only the onset of students' MR abilities but cannot determine their future mental abilities. Although the clinical-imaging interpretation skills of students improved (**Figures 6.39, 6.40**) with the use of Sectra, 3DP models, and 2D images, whether MR or spatial ability contributes to this improvement is unknown because relatively few students took the MR post-test in this study.

Another potential limitation is that the anatomical region in the intervention activity differed from that in the control activity. The study aim was to achieve consistency in the delivery of the material in the learning activities; however, consistency might have been affected by variations in the knowledge and approaches of the individual instructors. The instant post-test was able to show only short-term gains and improvement, and the delayed tests might have been subject to contamination because students might have been exposed to resources other than those included in the study.

8.2 Technological Limitations

The availability, ethical use, and consent to use the DICOM images for 3DP was a major problem faced in this study. Because of the limited access to the DICOM images, some 3DP models lacked several details. Low 3DP model numbers and long printing times owing to printer quality were considered a weakness of the study. We plan to use appropriate DICOM images to obtain high-quality models to eliminate this limitation. The 3D printed models used in the study were simple and had only one colour, thus representing another limitation. However, more detailed and complex 3DP models with more colours could be printed with an appropriate printer type and model (McMenamin et al., 2014; Li et al., 2017b). A lack of smoothness for 3DP models can result from the use of open-source software programmes such as Blender version 2.8 (Stitching Blender Foundation, Amsterdam, The Netherlands) and Meshmixer version 3.5 (Autodesk Inc., San Rafael, CA). Additionally, the design of 3DP models from DICOM images with these open resources required more time than the use of commercial software, such as Materialise, which provides a more managed and controlled process for designing 3D models.

Chapter 9. Conclusions

The goals of the study were addressed, and the research questions were answered. The study findings support the hypothesis that embryology and clinical cross-sectional-image interpretation are the main challenging areas for medical students. Implementing multimodal learning approaches including digital resources and 3DP models in cardiovascular practical sessions improves students' performance in the interpretation of clinical images and enhances their learning and experiences regarding thorax cross-sectional anatomy. The findings suggest that combining the appropriate resources, including 2D and 3D resources, improves visualisation and observation skills from multiple perspectives in learning anatomy and radiology; moreover, students' understanding of these challenging areas can be supported by providing digital and 3D resources. Interestingly, medical students' performance was shown to be independent of their MR abilities, thus potentially indicating that the clinical learning activities may help and benefit a diverse population of students with different spatial ability skill levels.

Furthermore, the study findings may provide a basis for designing and developing clinical-image-interpretation learning activities in anatomy curricula. Medical students had positive perceptions regarding the new resources. The findings also indicated that SEP, a remote digital resource, enhances medical students' gross anatomy and radiology learning, and supports their understanding of, and ability to identify, anatomical structures and features in cross-sectional clinical images. Moreover, remote access to SEP provides students with the flexibility and the freedom to study and review clinical images at their own pace. Having remote access to teaching resources encourages students to be accountable and responsible for their own learning.

Because embryology is considered a challenging area for medical students, digital embryology resources were implemented to enhance and improve students' understanding of 3D representation and embryonic development. Students had positive perceptions regarding the implementation of digital and interactive 3D models. The effects of the COVID-19 pandemic required a rapid transition to remote learning as an alternative to traditional teaching methods, thereby increasing the importance of remote resources.

The implementation of Sectra as a 3D digital resource, and 3DP models or similar approaches such as 3D digital remote resources and online games (Jamil et al., 2019), in learning activities is recommended to support students' learning of anatomy and clinical-image interpretation, regardless of their visuospatial abilities. The findings presented herein suggest that future investigations aiming to understand the relationships between anatomy learning, clinical-imaging interpretation, and spatial abilities would be beneficial.

Future recommendations include increasing the time allocated to clinical-image-interpretation learning activities, and providing more remote access resources. The outcomes of our work have wide implications regarding the planning and integration of 3D digital and online remote resources for anatomy students and instructors. Multimodal learning technologies and approaches can effectively supplement traditional teaching approaches, and radiology can be integrated within anatomy curricula for enhancing human anatomy education.

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Appendices

Appendix A (Ethics Committee Approval Letter)

Newcastle University

Faculty of Medical Sciences

Newcastle University
The Medical School
Framlington Place
Newcastle upon Tyne
NE2 4HH United Kingdom

Abdullah Ben Awadh
Institute of Genetic Medicine

FACULTY OF MEDICAL SCIENCES: ETHICS COMMITTEE

Dear Abdullah Ben Awadh,

Title: Digital and 3D approaches for enhancing human anatomy education
Application No: 1431/2095/2018
Start date to end date: 10/01/2018 to 09/10/2020

On behalf of the Faculty of Medical Sciences Ethics Committee, I am writing to confirm that the ethical aspects of your proposal have been considered and your study has been given ethical approval.

The approval is limited to this project: **1431/2095/2018.** If you wish for a further approval to extend this project, please submit a re-application to the FMS Ethics Committee and this will be considered.

During the course of your research project you may find it necessary to revise your protocol. Substantial changes in methodology, or changes that impact on the interface between the researcher and the participants must be considered by the FMS Ethics Committee, prior to implementation.*

At the close of your research project, please report any adverse events that have occurred and the actions that were taken to the FMS Ethics Committee.*

Best wishes,

Yours sincerely

K. Sutherland

Kimberley Sutherland
On behalf of Faculty Ethics Committee

cc.
Professor Daniel Nettle, Chair of FMS Ethics Committee
Mrs Kay Howes, Research Manager

*Please refer to the latest guidance available on the internal Newcastle web-site.

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Faculty of Medical Sciences

FMS Ethics Committee

Note of Guidance on Amendments to Ethical Approval

Amendments to Ethical Approval include an extension to the period of approval and an amendment to the research protocol.

1) To extend the period of approval

   The period of approval ends with the close of the original project. If there is to be an additional research question to answer or a follow-up study then a further period of ethical approval needs to be applied for. Please submit a reasoned request and further application to the FMS Ethics Committee.

   In your reasoned request and application please give your Ethics Approval code (given on the approval letter) together with the details of the proposed work and a new expected end date.

   This should be sent to: fmsethics@ncl.ac.uk.

2) To extend approval to accommodate a change in protocol

   During the course of carrying out your research it may be necessary to make substantial changes to the methodology or the way in which you interface with participants. For example you may need to include a different test or use a different piece of testing equipment, or significantly alter the number of tests a participant undertakes, or extend your recruitment of participants to include additional sources, or include additional pieces of information from participants in your consent form. These examples are not exhaustive.

   Any changes must be considered. If you are in any doubt about what would constitute a change, please seek advice from the FMS Research Office, please contact fmsethics@ncl.ac.uk.

   If you need to get your ethical approval extended to cover a changed protocol, please submit a request to the FMS Committee and this will be considered. Your request should be sent to: fmsethics@ncl.ac.uk.

   In your request please give your Ethics Approval code (given in your approval letter) together with all of the details of the changes that you have decided are necessary. From experience, the easiest way to demonstrate changes would be to amend the original application using "track changes" so that the new details and removal of old details is clearly shown. (Where the changes are limited to the consent form and information sheets it is just these, with the changes clearly shown, that need to be submitted.) This will save time in the process of considering the changes you require and facilitate a quicker response to you and minimise the delay to your work.

Faculty of Medical Sciences

FMS Ethics Committee

Note of Guidance on Reporting Adverse Events

At the close of your project, please ensure that any adverse events have been reported to the FMS Ethics Committee.

An adverse event is where a participant might have suffered negative experiences as a result of participating in your study. Adverse events might include expected and unexpected outcomes where researchers felt the need to help participants to deal with their negative experiences.

While adverse events may not be common, they may occur. If this is the case, then a brief summary of each event and the actions that were taken must be reported.

Your report must include your Ethics Approval code (given in your approval letter) and should be sent to: fmsethics@ncl.ac.uk.

Appendix B (Consent Form)

Dr. Iain Keenan (Supervisor) School of Medical Education (SME)

Abdullah Ben awadh (PhD Student) Institute of Genetic Medicine (IGM)

Anatomy and Clinical Skills Centre

Newcastle University

Newcastle upon Tyne NE2 4HH

Email:iain.keenan@newcastle.ac.uk / a.ben-awadh2@newcastle.ac.uk

Phone: (+44) 0191 208 6861

Student Consent Form

Project Title: Digital and 3D approaches for enhancing human anatomy education

IMPORTANT: PLEASE READ THE ATTACHED INFORMATION DOCUMENT CAREFULLY BEFORE ADDING YOUR PARTICIPANT NUMBER

If you consent to participate, please write your participant number below. Please keep the attached information document for reference to details of your participation in the research and issues of confidentiality and consent.

I agree that information gathered through this study will always be used anonymously for any research purposes including contributions to a doctoral thesis, for the ultimate aim of improving teaching and learning within medical education.

NAME: ___________________________________

STUDENT ID NUMBER (PARTICIPANT NUMBER):

____

Appendix C (Student participation and Information sheet)

STUDENT PARTICIPATION AND INFORMATION

Dr. Iain Keenan (Supervisor) School of Medical Education (SME)

Abdullah Ben awadh (PhD Student) Institute of Genetic Medicine (IGM)

Anatomy and Clinical Skills Centre

Newcastle University

Newcastle upon Tyne NE2 4HH

Email:iain.keenan@newcastle.ac.uk / a.ben-awadh2@newcastle.ac.uk

Phone: (+44) 0191 208 6861

Project Title: Digital and 3D approaches for enhancing human anatomy education

IMPORTANT: PLEASE READ CAREFULLY

We would like to invite you to participate in a research study with the aim to design, evaluate and develop innovative, creative and digital methods of medical student learning of clinical imaging, embryology and gross anatomy to identify the most effective approaches for implementation into medical curricula.

The research will involve any or all of the following: Investigation of the use of three-dimensional printing (3DP), a SECTRA anatomy visualisation table, digital embryology resources and/or other digital and 3D approaches. All these methods are intended to enhance medical sciences students learning and understanding of anatomy and to increase the variety of learning resources and quality of human anatomy education.

Research questions are as follows:

Which topics in gross anatomy, embryology and clinical imaging require a spatial understanding of anatomical features and processes in three-dimensions?

The learning of which three-dimensional concepts and processes in gross anatomy, embryology and clinical imaging do medical students find the most challenging?

Which digital and 3D approaches can enhance the learning of challenging three-dimensional concepts and processes in gross anatomy, embryology and clinical imaging?

To what extent do specific 3D and digital approaches enhance medical student perceptions and understanding of anatomy, embryology and clinical imaging?

The research will be conducted during timetabled or optional practical anatomy sessions, and participation in these sessions is optional.

You will be given a consent form for the experimental tests, questionnaires and focus groups separately, and you will have the choice to complete all or some of the above activities.

You will write your student ID number as your participant number when you participate in the research process.

Please keep this document for reference to details of your participation in the research and issues of confidentiality and consent.

Please carefully read the information below BEFORE agreeing to consent. This information is also provided when completing the experimental tests, questionnaires and focus groups.

Invitation to participate in a research study

The ability to interpret anatomical features in cross-sectional clinical images, and the ability to understand the three-dimensional and dynamic embryological processes involved human development, are two of the most challenging concepts experienced by students in their early years of medical school. The aim of this project is to design, evaluate and develop innovative, creative and digital methods of medical student learning of clinical imaging, embryology and gross anatomy to identify the most effective approaches for implementation into medical curricula. Current technological approaches can offer many advantages and benefits for both students and educators. The use of three-dimensional printing (3DP) can enhance understanding of the challenging topics to insure students satisfactions in terms of learning[1, 2]. One of our research aims is to show the role and benefits of 3DP models in medical curriculum. SECTRA is an anatomy visualisation Table consisting of a large interactive screen with an image display system that enables interaction with 3D human body images and CT or MRI Scans. SECTRA allows an Interactive learning and teaching platform with real-life anatomy and clinical cases which provide better understanding of the cross-sectional clinical image. The use of digital embryology resources that will involve painting and labelling 3D images of embryos at different stages of development to provide more effectiveness methods.

We aim to investigate the 3DP, SECTRA, digital embryology resources and other potential 3D methods (e.g. modelling clay) as new 3D learning methods by evaluating and understanding their value for enhancing students understanding of challenging topics in gross anatomy, clinical imaging and embryology.

We would like to invite medical sciences students to participate in this research by utilising the proposed methods, so we can find if these techniques can improve your learning.

We also aim to determine which the most effective method that will help you in making the mental transition between 2D clinical images and 3D anatomical structures.

All participant who give their consent to participate in the research can participate first with optional or timetabled practical sessions, depending on degree programme requirements. The sessions will be integrated in the research by lectures, seminars, self-directed online learning. The sessions will involve teaching topics in gross anatomy or embryology using the standard methods such as cadavers and the prosections specimens and our new technology (e.g. SECTRA ,3DP models and digital embryology resource). The new methods will be used in the sessions to provide better understanding for challenging topics. The participants will be tested, given a questionnaire, and invited to attend a focus group facilitated by a project researcher to discuss your experiences. The data obtained from the experimental tests will be statistically analysed. The questionnaires and the recorded focus groups will be analysed by thematic analysis to identify important themes arising from your perceptions to the new methods.

Your consent to participate is optional and you can withdraw at any time without detriment to yourself: By participating in the questionnaires, test questions and focus groups, you agree for the data from your responses to be used in the research. The research practical sessions will take place during some timetabled session and some optional practical sessions, but participation is completely optional.

You can withdraw from the research at any time by NOT answering questions and/or leaving the research practical sessions or focus group when you wish.

If you are unable to attend these sessions please inform the researchers (iain.keenan@newcastle.ac.uk and a.ben-awadh2@newcastle.ac.uk), so Information about each session can then be provided to you so you can use the process for self-study of the topic and learning outcomes.

If you are able to attend the session but you are unable to participate (e.g. due to a physical impediment), please inform the researchers (iain.keenan@newcastle.ac.uk and a.ben-awadh2@newcastle.ac.uk) and arrangements will be made for you to be assisted by a demonstrator.

Confidentiality and use of data:

Your answers to the experimental tests (pre, post and delayed), questionnaires and focus groups, and research results of your participation will be kept anonymous and confidential.

We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name.

Your responses to tests questions and questionnaires and your participation in the focus groups will be used for RESEARCH and NOT FOR ASSESSMENT. Data will also be used in a doctoral thesis. Your responses will only be used for research, in dissertations and/or publications WITH YOUR CONSENT. When the research is published or submitted as a dissertation, you will not be identified by name or student number. We cannot guarantee that the research will be accepted for publication or submitted as a dissertation.

If you have any further questions about the research, please contact

Dr. Iain Keenan (Supervisor) (School of Medical Education)

Email: iain.keenan@newcastle.ac.uk

Abdullah Ben awadh (PhD Student) Institute of Genetic Medicine (IGM)

Email: a.ben-awadh2@newcastle.ac.uk

Anatomy and Clinical Skills Centre

Newcastle University, Newcastle upon Tyne NE2 4HH, Phone: (+44) 0191 208 6861

References:

1. Smith, C.F., et al., *Take away body parts! an investigation into the use of 3D-printed anatomical models in undergraduate anatomy education.* Anatomical Sciences Education, 2017: p. n/a-n/a.

2. Lim, K.H.A., et al., *Use of 3D printed models in medical education: A randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy.* Anatomical Sciences Education, 2016. 9(3): p. 213-221.

Appendix D (Challenging Topics Questionnaire)

Challenging Topics Questionnaire

Thank you for taking the time to complete this questionnaire, your participation is very much appreciated.

Name:

Student ID number (Participation number):

Please read the question carefully:

I. Demographics

Gender

☐ Male | ☐ Female

Age

☐ (17-20) | ☐ (21-24)| ☐ (25-28)| ☐ (29-32)| ☐ (33-36)

Educational Level

☐ (Further Education – e.g. A-levels) | ☐ (Bachelor Degree)| ☐ (Master Degree)| ☐ (PhD)

Do you have any previous experience of anatomy education other than your current degree? If yes please provide more details.

☐ No | ☐ Yes

Do you have any previous work experience relating to anatomy and/or clinical imaging? If yes please provide more details.

☐ No | ☐ Yes

II. Gross Anatomy

From question 1 to question 3 Please tick the most appropriate answer for each question, where 1 is Strongly Disagree and 7 is Strongly Agree.

1- Gross Anatomy is a valuable and important component of my current degree.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

2- Gross anatomy is a challenging component of my current degree when compared to the other basic sciences (e.g. physiology, biochemistry, genetics, etc.).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

3- There are particular aspects of anatomy learning within my current degree that are more challenging than others.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

For the following items (questions 4 to 9) Please tick the most appropriate number for each question, where 1 is Not at all challenging, and 7 is Extremely challenging

4- From your own experience of your current degree, how challenging has it been to learn the following anatomical topics? (1 is not at all challenging and 7 is extremely challenging)

A-	Gross Anatomy	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Embryology	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Clinical imaging	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Microanatomy	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	Histology	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

5- From your own experience of your current degree, how challenging has it been to learn the following anatomical regions? (1 is not at all challenging and 7 is extremely challenging)

A-	Abdomen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Thorax	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Head and Neck	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Pelvis and Perineum	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	Limbs	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

6- From your own experience of your current degree, how challenging has it been to understand the gross anatomical structure of the following visceral organs? (1 is not at all challenging and 7 is extremely challenging)

A-	Heart	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Brain	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Kidney	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Liver and Gallbladder	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	Lungs	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
F-	Gut	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
G-	Pancreas	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

7- From your own experience of your current degree, how challenging has it been to understand the anatomy of the following features? (1 is not at all challenging and 7 is extremely challenging)

A-	Pericardial sac and sinuses	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Pleural cavity and its reflections/boundaries	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Peritoneum and its reflections/boundaries	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Inguinal canal	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

8- From your own experience of your current degree, how challenging has it been to understand the anatomy of the following gross structures? (1 is not at all challenging and 7 is extremely challenging)

A-	Fascia	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Muscles and tendons	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Bones and ligaments	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Organs	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	Blood vessels	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
F-	Nerves and plexuses	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

9- From your own experience of your current degree, how challenging has it been to identify the anatomy of the following anatomical features in cross-sectional images? (1 is not at all challenging and 7 is extremely challenging)

A-	Muscles Compartments	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Heart	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Liver	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Abdomen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

Please comment on any other feature(s) you find particularly challenging (i.e. other features that you would rank as 6 or 7 in the scale above) (free-text item):

For the following items (questions 10 to 12) Please tick the most appropriate number for each question, where 1 is strongly disagree, and 7 is strongly agree.

10- From your own experience of your current degree, which of the following resources do you think would provide added value to your self-directed learning of anatomy? (1 is strongly disagree and 7 is strongly agree)

A-	Self-directed learning with SECTRA	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Self-directed learning with 3D printed organs	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Self-directed learning with an online interactive digital embryology resource	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

11- From your own experience of your current degree, which of the following reasons make gross anatomy challenging to understand: (1 is strongly disagree and 7 is strongly agree)

A-	Volume of content to learn	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Teaching contact time	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Lack of appropriate and effective resources	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Anatomical terminology	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	3D Spatial relationships of anatomical structures	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
F-	Interpretation of 3D anatomical features in 2D cross-sectional Images	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

12- From your own experience of your current degree, development of which of the following skills do you think would enhance your learning of gross anatomy (1 is strongly disagree and 7 is strongly agree)

A-	Spatial ability	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Visual observation of anatomical features	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Haptic observation (touch)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Knowledge retention (memory)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	Making connections in your understanding of different anatomical structures	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

13- Please describe any other challenging areas, topics or concepts you have encountered in your learning of gross anatomy that have not mentioned above. (Free-text item).

14- Please describe any additional taught or self- directed resources that you feel would enhance your anatomy learning further to the resources you currently use. (Free-text item)

III. Clinical Imaging:

From your own experience of your current degree, please describe any challenging areas, topics or concepts you have encountered when attempting to interpret anatomical features in cross-sectional clinical images. (Free-text item).

If you like to participate in a focus group discussion of some of the areas covered in this questionnaire), please provide your email and we will contact you.

Email: ____

Thanks for Participating and we do appreciate your effort…

Participant consent and use of data

We have developed this questionnaire in order to obtain Newcastle University student perceptions regarding the most challenging topics in anatomy learning. The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the questionnaire items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name. By submitting this questionnaire, you are consenting for your data to be used for research purposes. Do not submit the questionnaire if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan (iain.keenan@newcastle.ac.uk)

Abdullah Ben awadh (a.ben-awadh2@newcastle.ac.uk)

Appendix E (Focus group questions for Phase I)

Focus Group Questions

Focus Group (Challenging Topics):

Welcoming the participants

A Brief information about the project in general and about the focus group in particular.

Opening Questions:

Is anatomy an important component of your current degree and why?

Comparing to other basic sciences is gross anatomy a challenging component of your current degree?

Introductory Question:

Do you think that there are challenging topics in gross anatomy and why?

Transition Questions

Form your experience, which of the following topics you think is the most challenging and why? (Gross Anatomy, Clinical Imaging, Embryology, Histology, Microanatomy)

Key Questions:

Which anatomical region you find it the most challenging and why?

Can anyone tell me, the most challenging visceral organs to understand it's structures and functions?

Are there difficulties in interpretation and understanding the anatomical features in cross sectional images?

From your experience, do you think 3DP, SECTRA and Digital Embryology Resources will help you with self-directed learning of anatomy?

Do you think that the development of some skills can enhance your learning of anatomy? And if yes what are these skills?

Ending Question:

Thank you for taking the time to participate in this discussion group, and is there any more information you would like to add that haven't been discussed?

Appendix F (Challenging Topics, Sectra And 3DP Questionnaire)

Challenging Topics, Sectra And 3DP Questionnaire

Thank you for taking the time to complete this questionnaire, your participation is very much appreciated.

Name:

Student ID number (Participation number):

Please read the question carefully:

I. Demographics

1- Gender

☐ Male | ☐ Female

2- Age

☐ (17-20) | ☐ (21-24)| ☐ (25-28)| ☐ (29-32)| ☐ (33-36)

3- Educational Level

☐ (Further Education – e.g. A-levels) | ☐ (Bachelor Degree)| ☐ (Master Degree)| ☐ (PhD)

4- Do you have any previous experience of anatomy education other than your current degree? If yes please provide more details.

☐ No | ☐ Yes

Do you have any previous work experience relating to anatomy and/or clinical imaging? If yes please provide more details.

☐ No | ☐ Yes

II. Gross Anatomy

From question 1 to question 3 Please tick the most appropriate answer for each question, where 1 is Strongly Disagree and 7 is Strongly Agree.

1- Gross Anatomy is a valuable and important component of my current degree.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

2- Gross anatomy is a challenging component of my current degree when compared to the other basic sciences (e.g. physiology, biochemistry, genetics, etc.).

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

3- There are particular aspects of anatomy learning within my current degree that are more challenging than others.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

For the following items (questions 4 to 6) Please tick the most appropriate number for each question, where 1 is Not at all challenging, and 7 is Extremely challenging

4- From your own experience of your current degree, how challenging has it been to learn the following anatomical topics? (1 is not at all challenging and 7 is extremely challenging)

A-	Gross Anatomy	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Surface Anatomy	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Clinical imaging	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

5- From your own experience of your current degree, how challenging has it been to learn the following anatomical regions? (1 is not at all challenging and 7 is extremely challenging)

A-	Abdomen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Thorax	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

6- From your own experience of your current degree, how challenging has it been to understand the gross anatomical size, shape, position and structure of the following anatomical features? (1 is not at all challenging and 7 is extremely challenging)

A-	Heart	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Kidney	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Peritoneum	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

For the following items (questions 7 to 8) Please tick the most appropriate number for each question, where 1 is strongly disagree, and 7 is strongly agree.

7- From your own experience of your current degree, which of the following make learning gross anatomy challenging: (1 is strongly disagree and 7 is strongly agree)

A-	Volume of content to learn	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Teaching contact time	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Lack of appropriate and effective resources	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Anatomical terminology	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	3D Spatial relationships of anatomical structures	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
F-	Interpretation of 3D anatomical features in 2D cross-sectional Images	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

8- From your own experience of your current degree, development of which of the following skills do you think would enhance your learning of gross anatomy (1 is strongly disagree and 7 is strongly agree)

A-	Spatial ability	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Visual observation of anatomical features	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
C-	Haptic observation (touch)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
D-	Knowledge retention (memory)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
E-	An overview of anatomical regions, structures and relationships	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

9- Please describe any other challenging areas, topics or concepts you have encountered in your learning of gross anatomy that have not mentioned above. (Free-text item)

10- Please describe any additional taught or self- directed resources that you feel would enhance your gross anatomy learning further to the resources you currently use. (Free-text item)

III. Clinical Imaging:

11- From your own experience of your current degree, how challenging has it been to identify the anatomy of the following anatomical features in cross-sectional images? (1 is not at all challenging and 7 is extremely challenging)

A-	Thorax	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
B-	Abdomen	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7

Please comment on any other feature(s) you find particularly challenging (i.e. other features that you would rank as 6 or 7 in the scale above) (free-text item):

IV. Sectra Usage

From question 1 to question 7 Please tick the most appropriate answer for each question, where 1 is Strongly Disagree and 7 is Strongly Agree.

1- The Sectra improved my understanding of the three-dimensional gross anatomy of the thorax.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

2- The Sectra improved my understanding of the gross anatomy of thorax in cross-sectional images.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

3. Physically interacting with the Sectra screen was important in improving my understanding of anatomy and cross-sectional images (please leave blank if you did not interact with the screen)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

4. If you physically interacted with the Sectra screen, please briefly describe why this interaction was/was not important in improving your understanding of anatomy and cross-sectional images

----

5- The Sectra was more valuable for my learning of gross anatomy and clinical image interpretation than using static 2D cross-sectional images.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

6- I found the 3D rendered images on Sectra valuable for my learning

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

7- Sectra would be a useful self-directed learning resource for studying three-dimensional and cross-sectional gross anatomy.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

8- Do you have any suggestions on how we can improve the use of Sectra?

V. 3D Printed (3DP) Models Usage

From question 1 to question 7 Please tick the most appropriate answer for each question, where 1 is <u>Strongly Disagree</u> and 7 is <u>Strongly Agree</u>.

1- Using the 3DP models during the practical session was valuable for my learning.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

2- The use of 3DP models improved my 3D understanding of the kidney.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

3- Using 3DP models outside of the DR would be a valuable self-directed learning resource for studying anatomy.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

Do you have any suggestions on how we can improve the use of 3DP models?

If you like to participate in a focus group discussion of some of the areas covered in this questionnaire), please provide your email and we will contact you.

Email: ____

Thanks for Participating and we do appreciate your effort…

Participant consent and use of data

We have developed this questionnaire in order to obtain Newcastle University student perceptions regarding the most challenging topics in anatomy learning and regarding the use of SECTRA and 3DP models in anatomy learning. The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the questionnaire items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name. By submitting this questionnaire, you are consenting for your data to be used for research purposes. Do not submit the questionnaire if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan (iain.keenan@newcastle.ac.uk)

Abdullah Ben awadh (a.ben-awadh2@newcastle.ac.uk)

Appendix G (Mental Rotation Test)

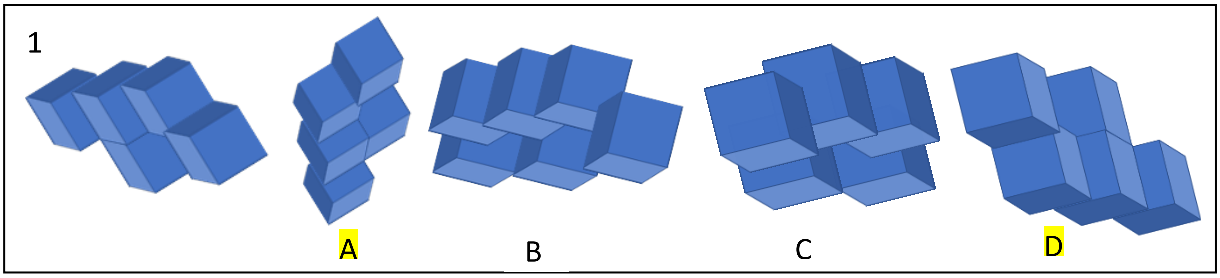
Mental Rotation Test:

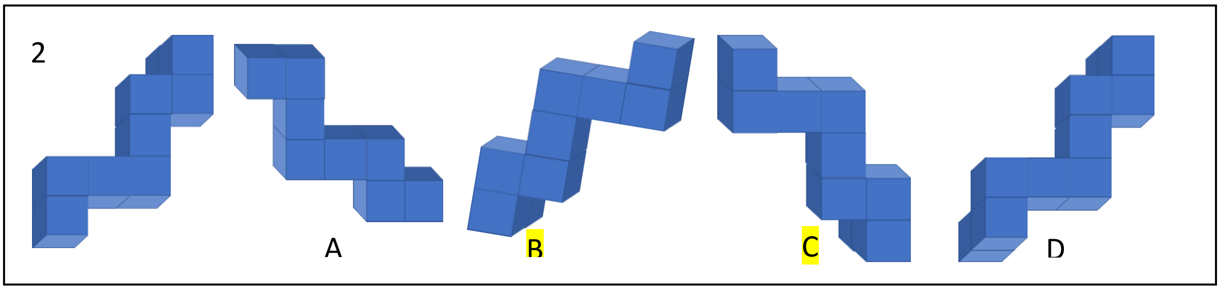
Name: ___________________________________

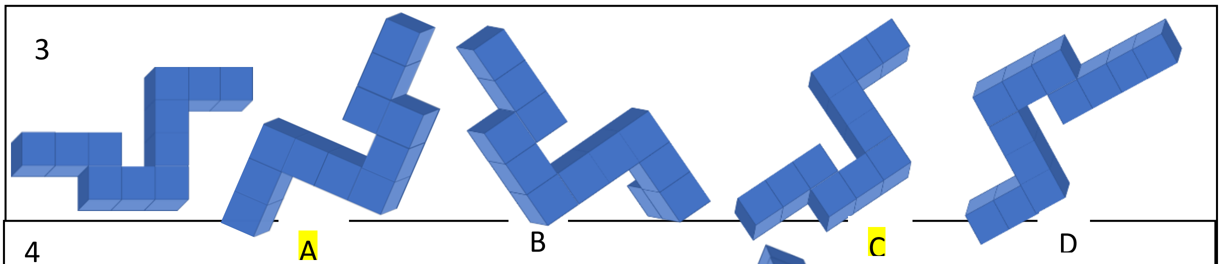
Student ID number (Participation number): _____________________________

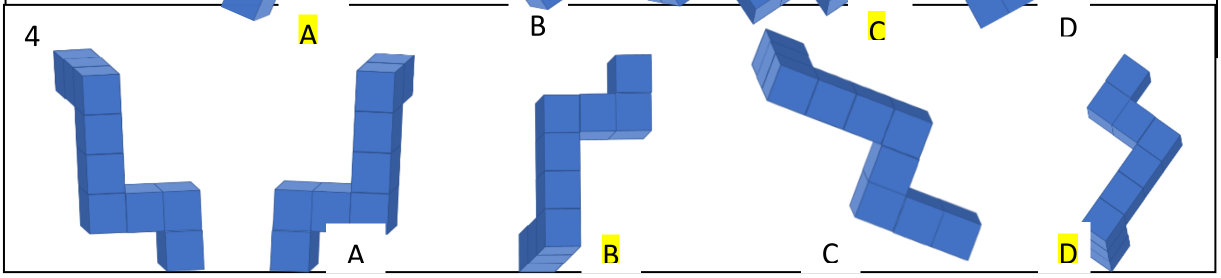
Please read the following instructions carefully.

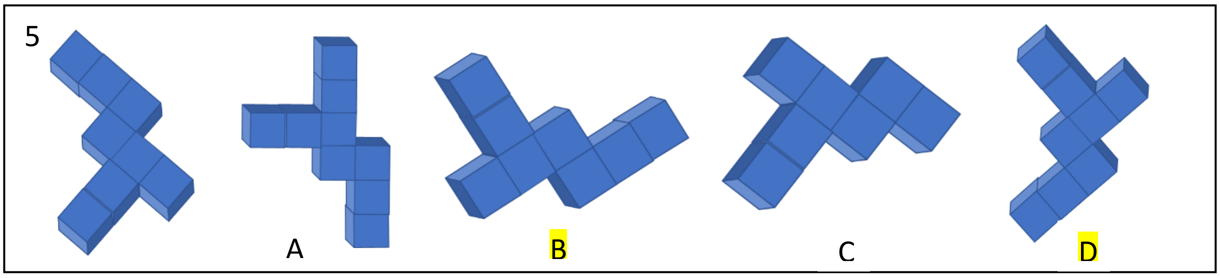
There are 10 questions to follow, please try and complete them all. For each question you will see 1 reference 3D shape followed by 4 similar looking 3D shapes. 2 of those 4 shapes are rotations of the reference shape, 2 are NOT and are different shapes. Identify the 2 that ARE rotations of the reference shape. You will only get a mark if you identify both correctly. The correct answers highlighted with yellow

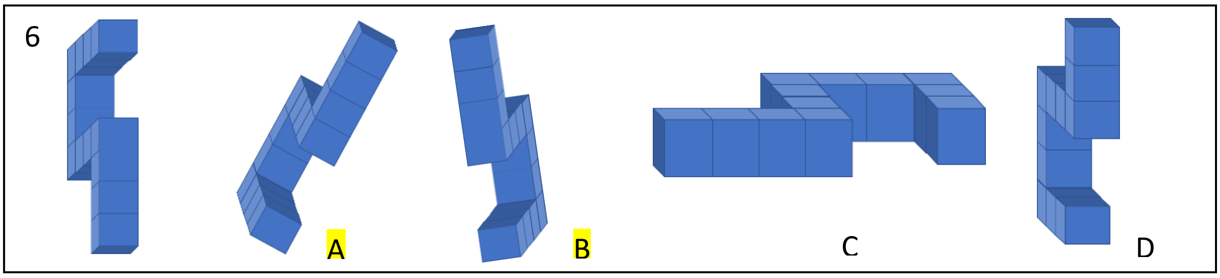


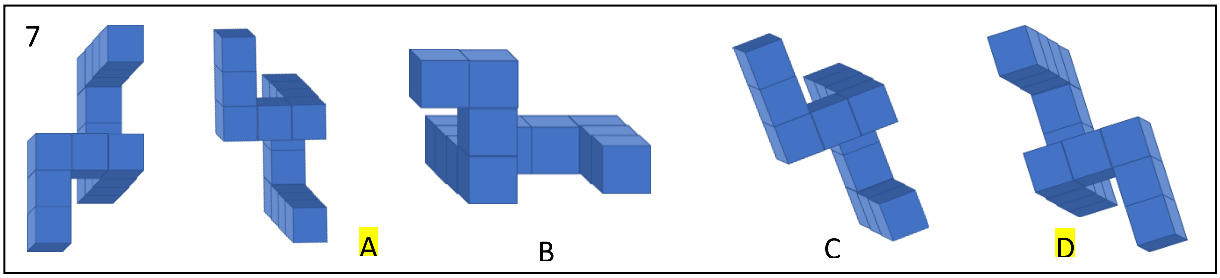


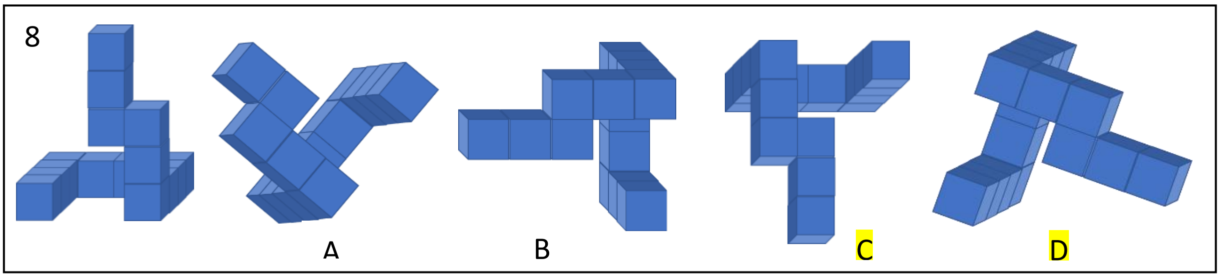


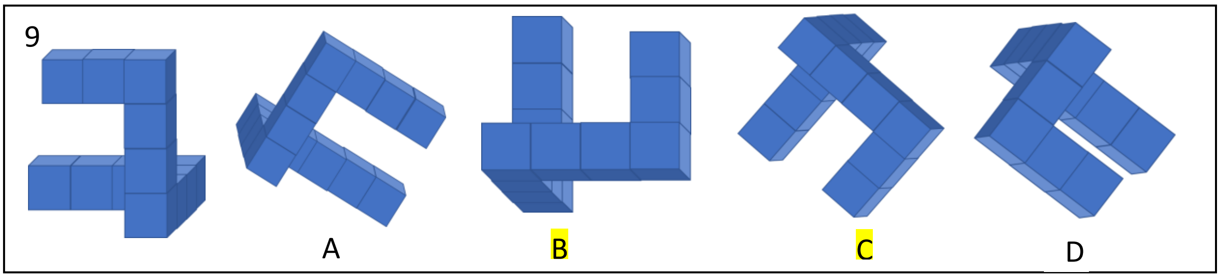


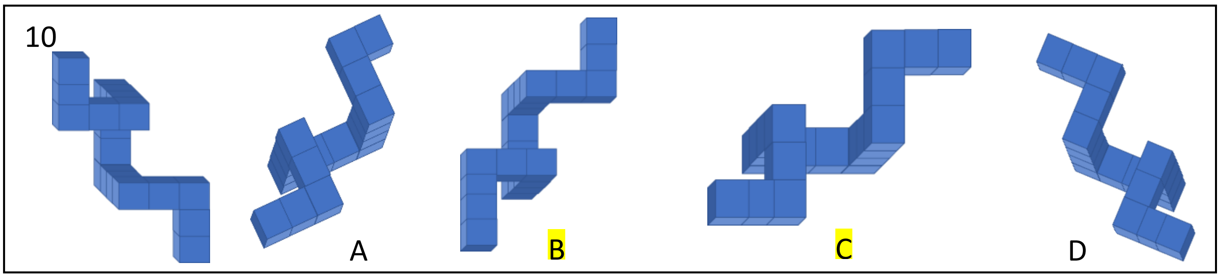

5
A
B
C
D


6
A
B
C
D


7
A
B
C
D


8
A
B
C
D


9
A
B
C
D


10
A
B
C
D

Thanks for Participating and we do appreciate your effort…

Participant consent and use of data

We have developed this test in order to obtain Newcastle University student perceptions and understanding regarding their spatial abilities. The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the test items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name. By submitting this test, you are consenting for your data to be used for research purposes. Do not submit the test if you do not consent for us to use your data for research purposes. For more information, please contact us by the email provided below.

Dr. Iain Keenan (iain.keenan@newcastle.ac.uk)

Abdullah Ben awadh (a.ben-awadh2@newcastle.ac.uk)

Appendix H (Sectra practical session task sheet (Thorax):

• To access the cases go to > PUBLIC CASES> System Worklist >Case by Body Regions > Thorax or write the case number in the search area.

• The students will hold the heart 3Dp models during the Sectra session.

Access these case (S011, S113)

Make sure for each case you access the 3D render option and check all bookmarks.

• Use three fingers to scroll up and down

• Use two fingers to zoom in and out

• Use one finger to adjust the contras

Identify the following features of the heart on the SECTRA:

Pulmonary veins

Superior vena cava

Inferior vena cava

Right atrium

Right ventricle

Aorta

Pulmonary trunk

Pulmonary arteries

Left atrium

Left ventricle

The base of the heart

Aortic arch

Features of the heart on radiograph and cross-sectional images

Left subclavian

R brachiocephalic artery

L Common carotid artery

Appendix I (Sectra + 3DP learning activity pre-test)

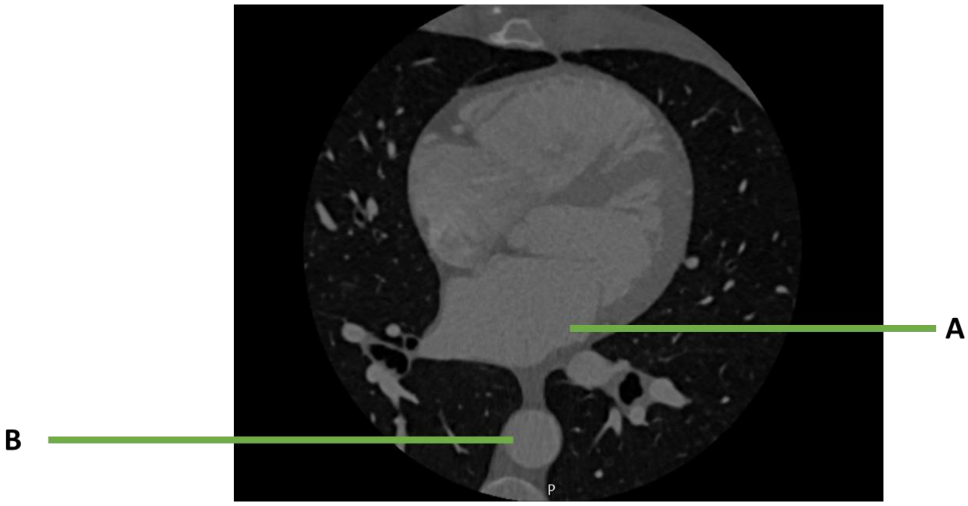
Pre-test Clinical imaging questions:

Name: ___________________________________

Student ID number (Participation number): _____________________________

LEARNING OUTCOME: Describe and identify the major features of the heart on cross sectional images

The test includes 12 identification questions with one or two questions under each image.

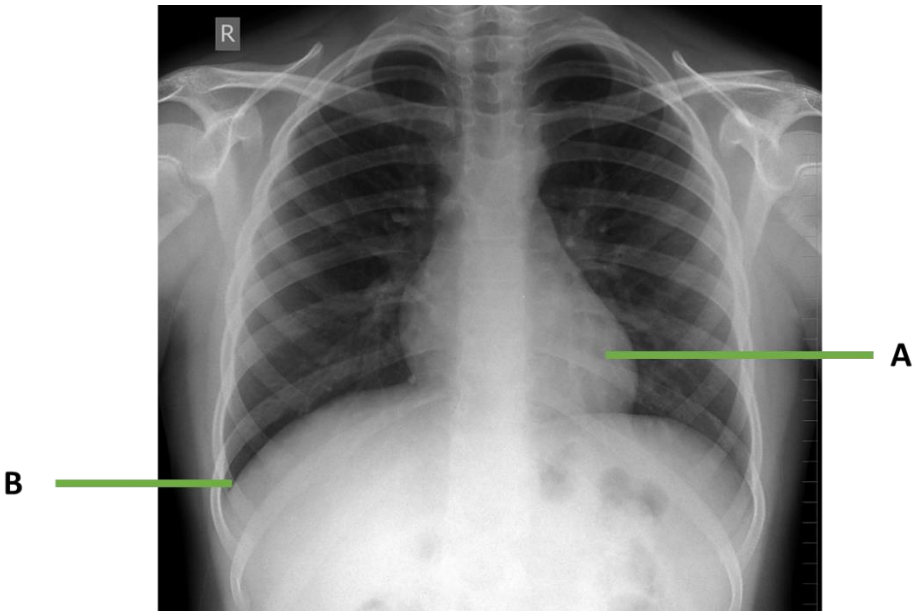


What is indicated by A?

Left Atrium

What is indicated by B?

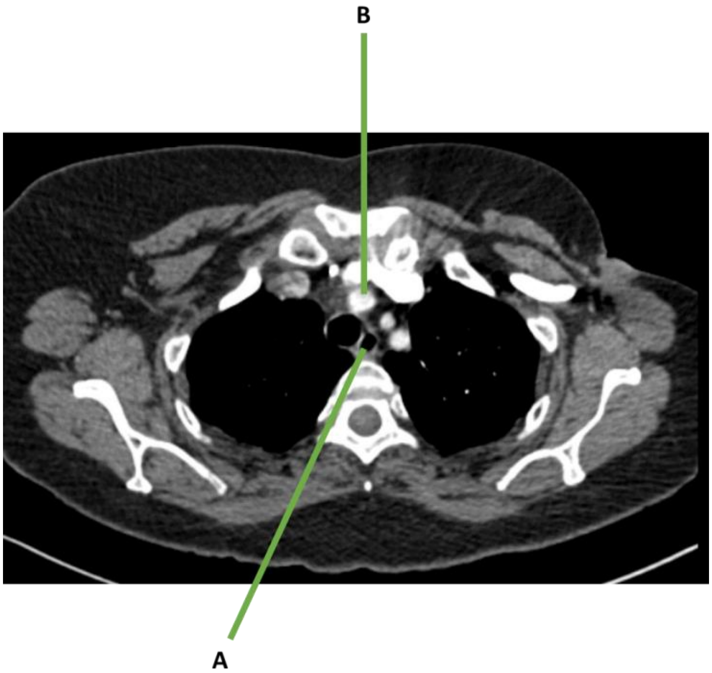
Descending Aorta



Identify A?

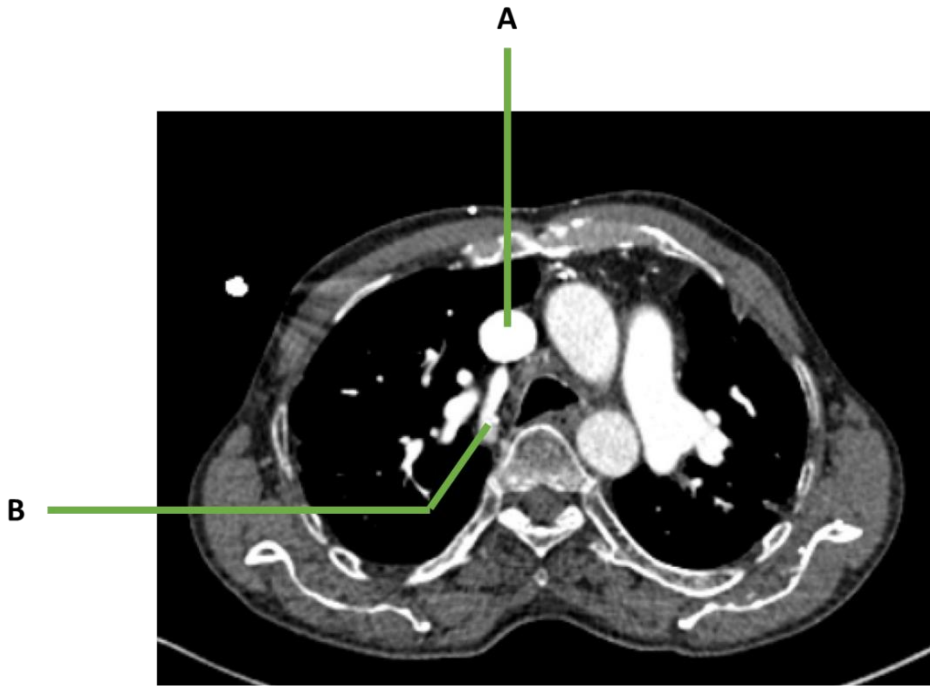
Left Ventricle

Identify B? Right Costophrenic Angle



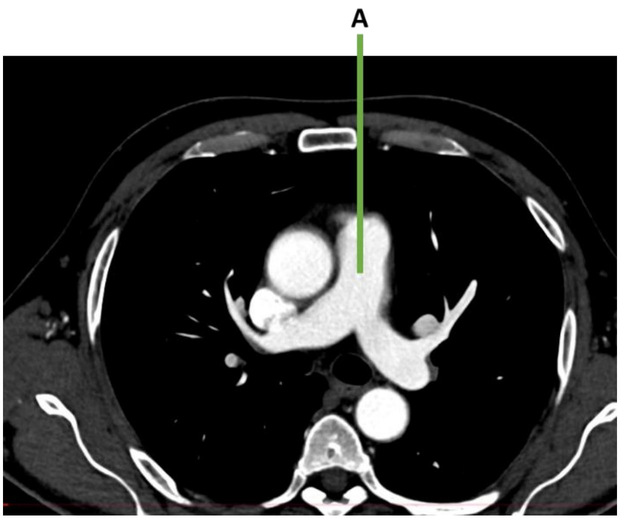
What is indicated by A? Brachiocephalic Artery

What is indicated by B? oesophagus

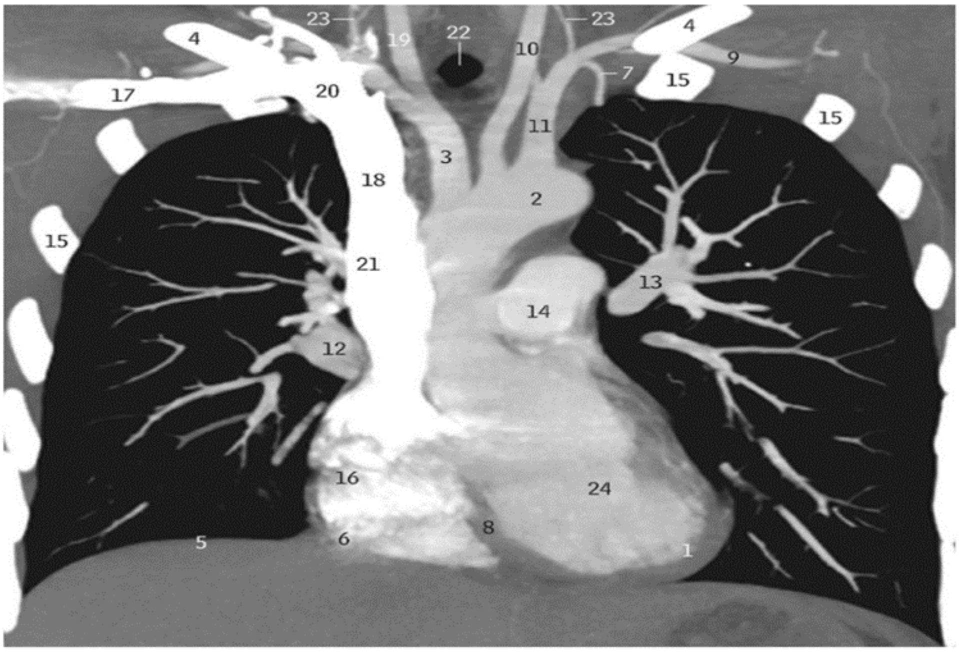


Identify the vein indicated by A? Superior Vena Cava

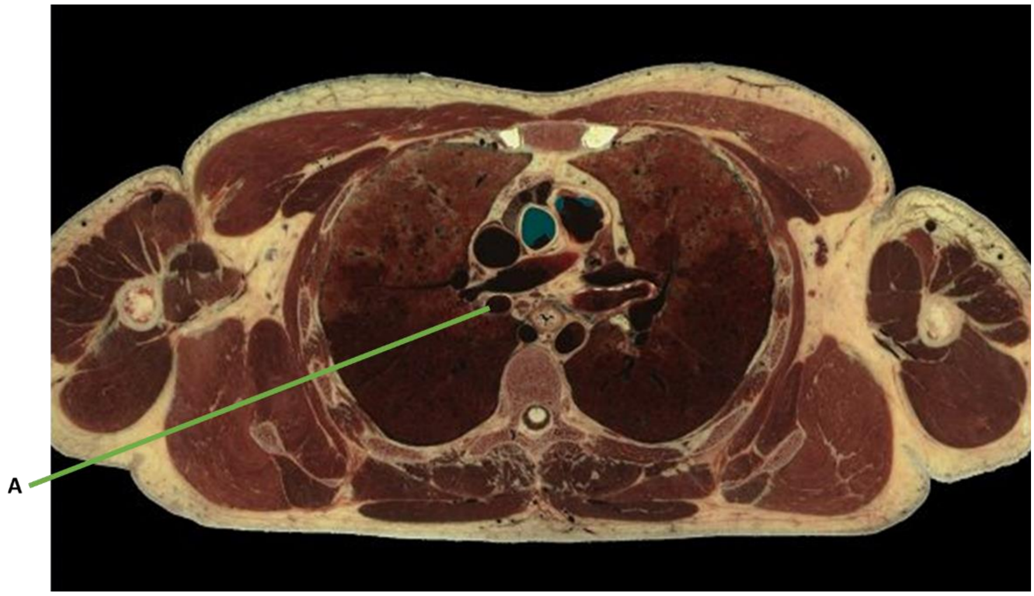
Identify the vein indicated by B? Azygous Vein



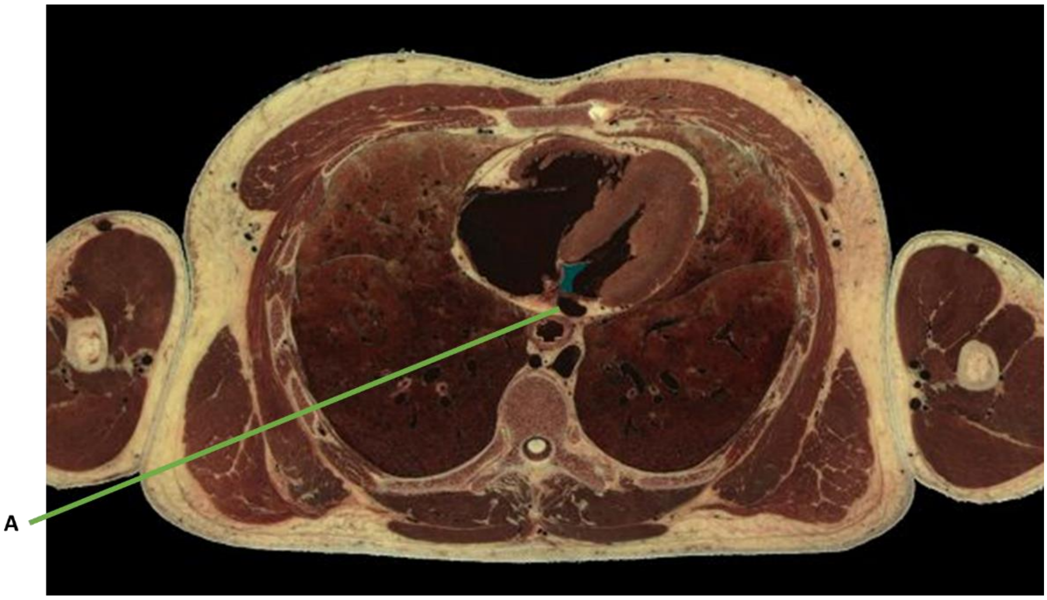
Identify the artery indicated by A? Pulmonary Trunk



What is indicated by 8? Interventricular septum



What is indicated by A? Right main Bronchus



What is indicated by A? Coronary Sinus

Thanks for Participating and we do appreciate your effort…

Participant consent and use of data

We have developed this test in order to obtain Newcastle University student perceptions regarding the use of SECTRA in anatomy learning. The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the test items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name. By submitting this test, you are consenting for your data to be used for research purposes. Do not submit the test if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan (iain.keenan@newcastle.ac.uk)

Abdullah Ben awadh (a.ben-awadh2@newcastle.ac.uk)

Appendix J (Sectra + 3DP learning activity post-test)

Newcastle University

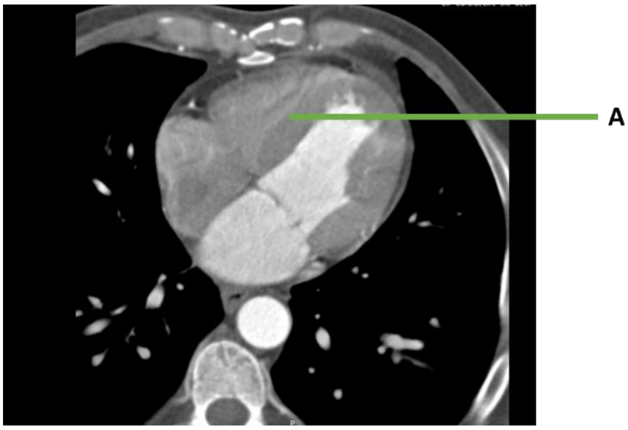
Post-test Clinical imaging questions:

Name: ___________________________________

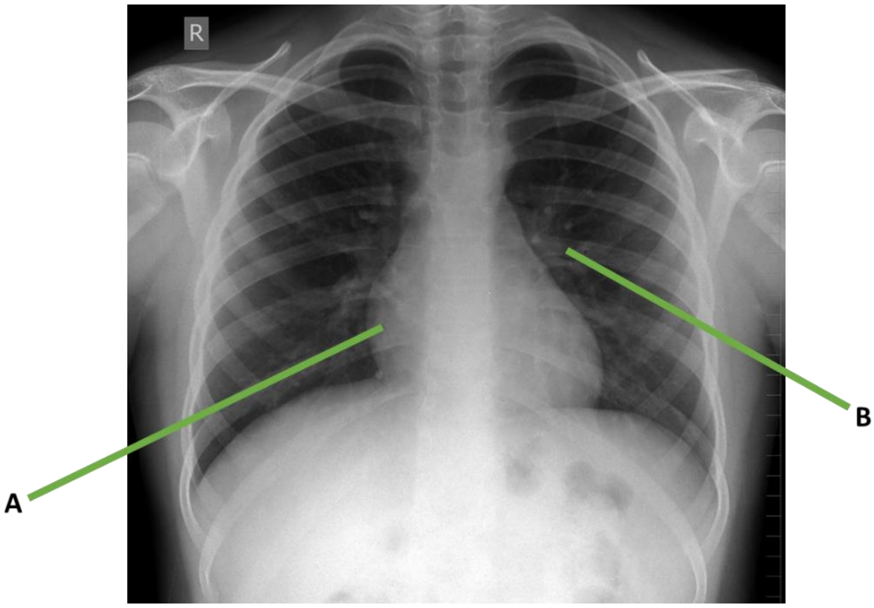
Student ID number (Participation number): ____________________________

LEARNING OUTCOME: Describe and identify the major features of the heart on cross sectional images

The test includes 12 identification questions with one or two questions under each image.

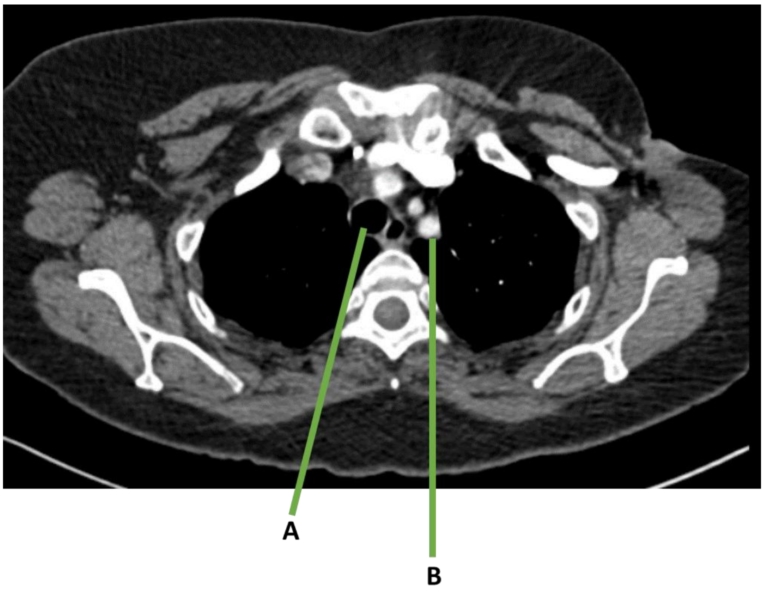


What is indicated by A? Right Ventricle



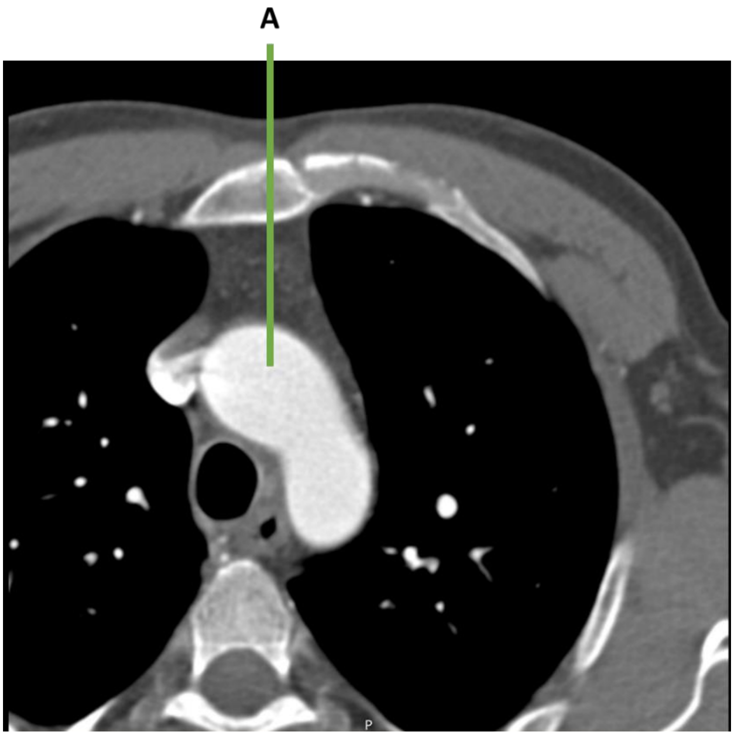
Identify A? Right Atrium

Identify B? Pulmonary Artery

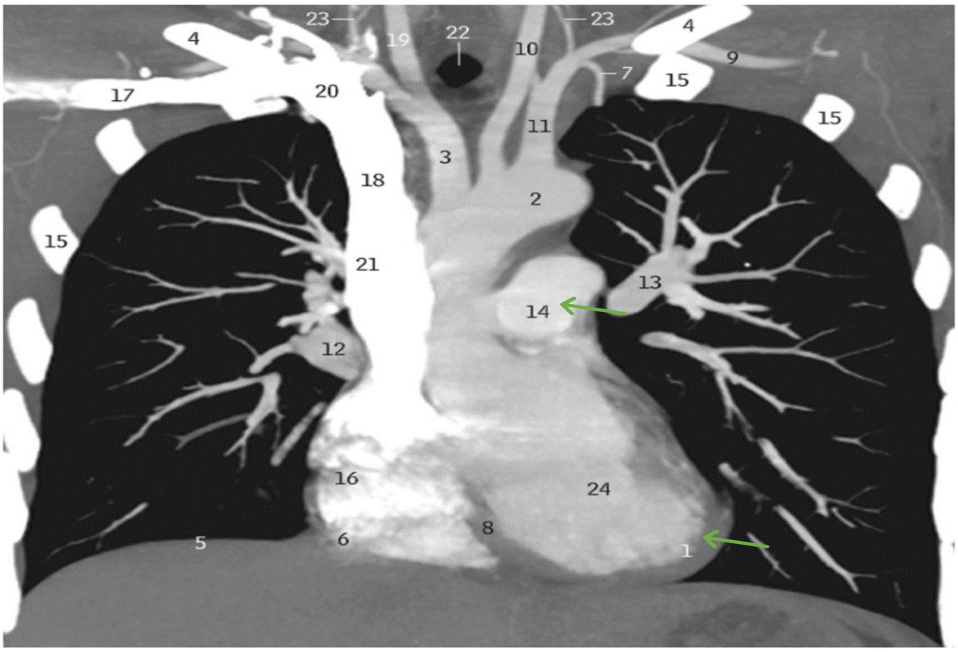


What is indicated by A? Trachea

What is indicated by B? Left Subclavian artery

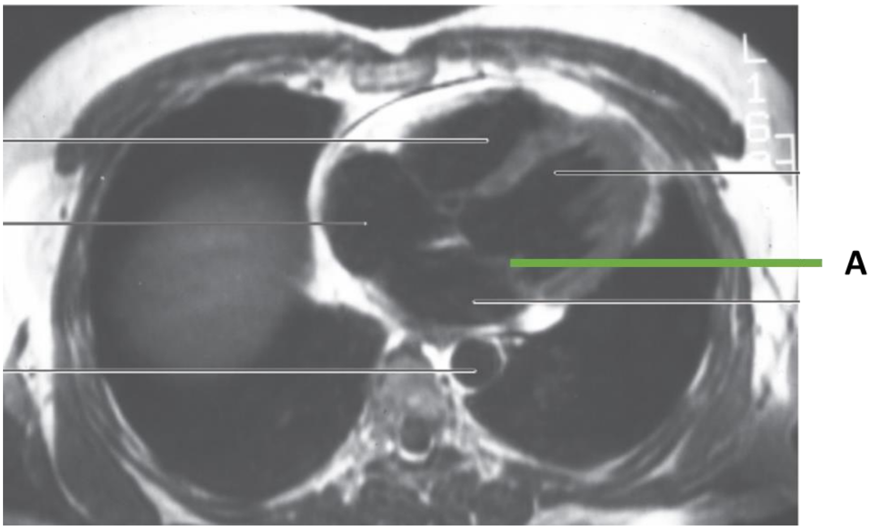


Identify what is indicated by A? Aortic Arch

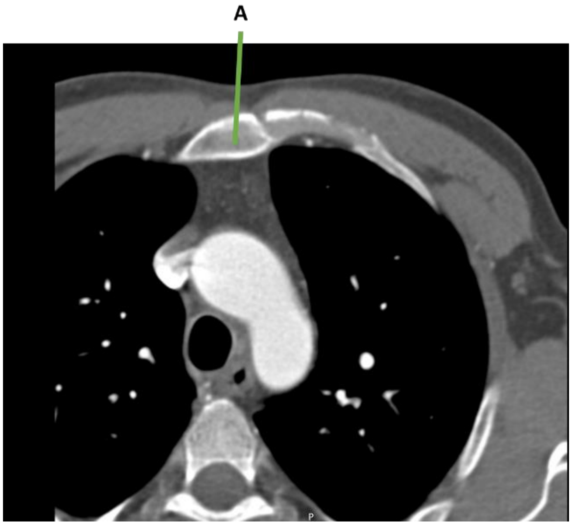


Identify the vein indicated by 14? Pulmonary Trunk

What is indicated by 1? Apex



Identify the valve indicated by A? Bicuspid Valve (Mitral)



Name the bone indicated by A? Sternum

What is indicated by A? Left Ventricle (myocardium)

What is indicated by A? oesophagus

Thanks for Participating and we do appreciate your effort…

Participant consent and use of data

We have developed this test in order to obtain Newcastle University student perceptions regarding the use of SECTRA in anatomy learning. The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the test items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name. By submitting this test, you are consenting for your data to be used for research purposes. Do not submit the test if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan (iain.keenan@newcastle.ac.uk)

Abdullah Ben awadh (a.ben-awadh2@newcastle.ac.uk)

Appendix K (2D learning activity task sheet)

<u>ABDOMINAL AND PERITONEAL CAVITY</u>

Access the VHD software on the PC.

Press of the Icon view on the top left corner.

Choose the transvers plane.

Scroll up and down by moving the square on the human body image on your right.

Strat with slice number 472 and scroll down to slice number 781.

<u>Identify the following features of the ABDOMINA AND PERITONEAL CAVITY</u>

Right lobe of liver

Left lobe of liver

Gallbladder

Inferior vena cava

Aorta

Superficial fascia (Campers – Fatty layer)

Oesophagus

Stomach

Pyloric orifice

Diaphragm

Azygos vein

Spleen

Hepatic Portal vein

Kidney

Small intestine

Pancreas

Transverse colon

Ascending colon

Descending colon , Cecum

Appendix L (2D learning activity pre-test)

Pre-test Clinical imaging questions:

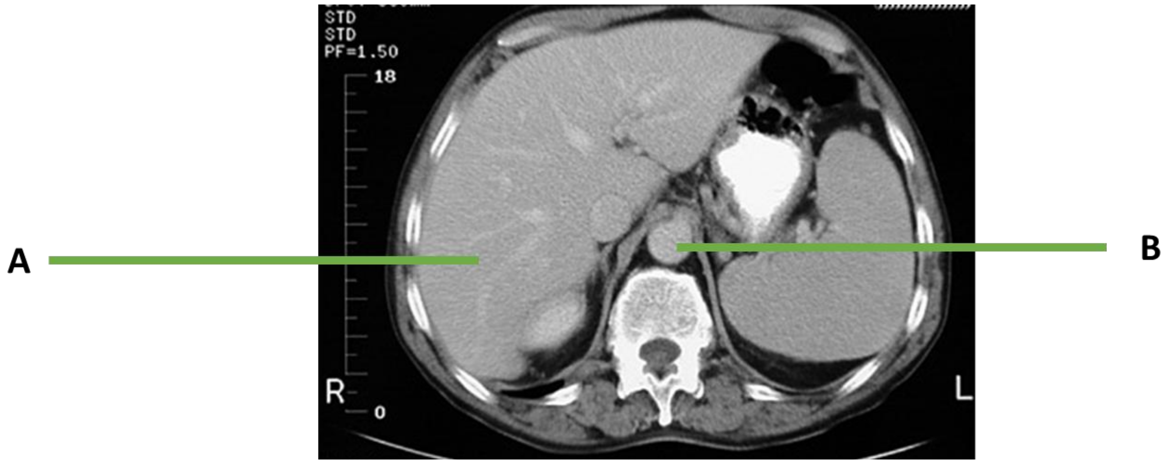
Name: ________________________________

Student ID number (Participation number): ___________________________

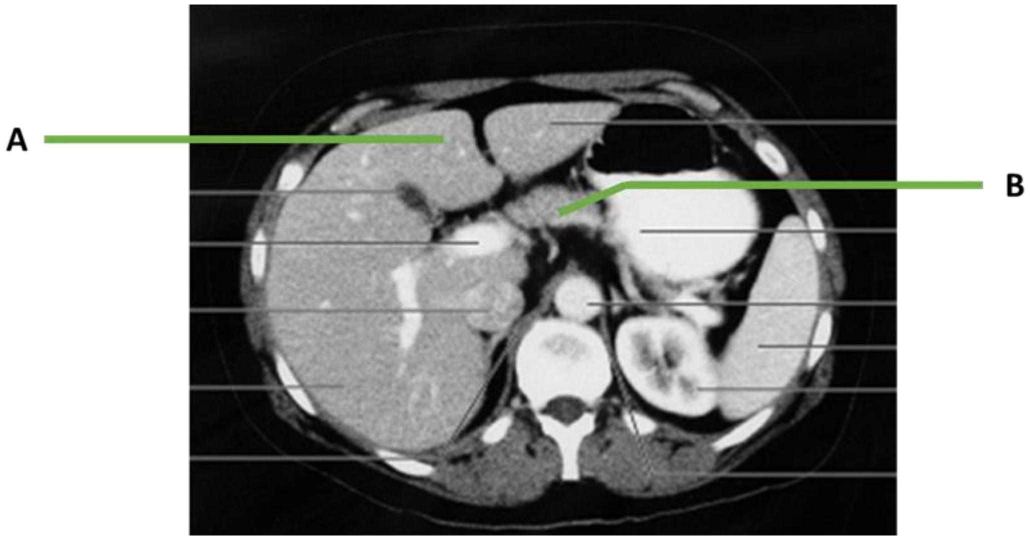
LEARNING OUTCOME: Describe and identify the abdominal viscera

The test includes 12 identification questions with one or two questions under each image

What is indicated by A? Right lobe of the Liver

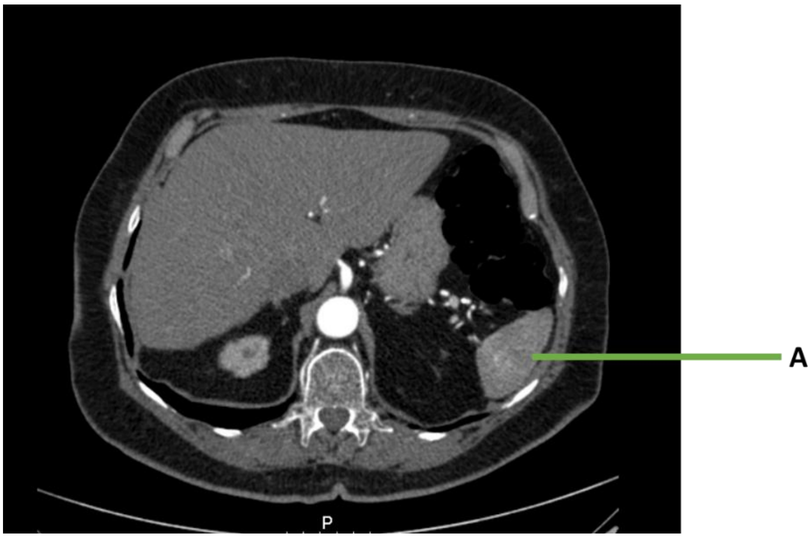


What is indicated by B? Aorta

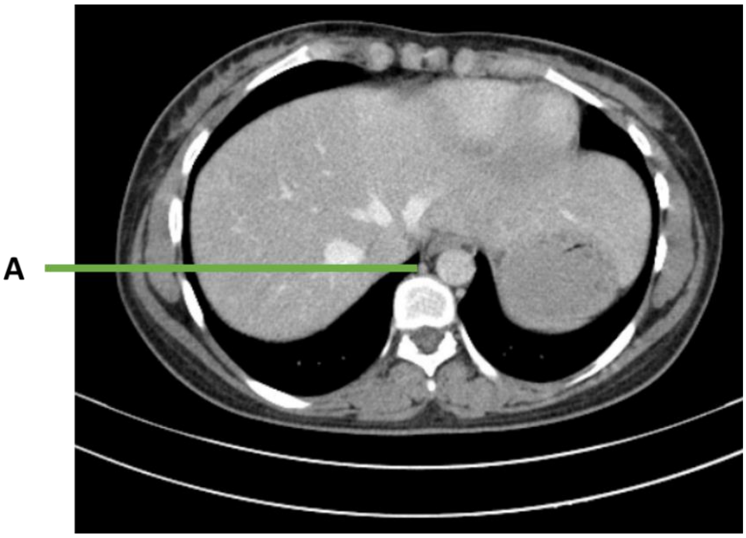


What is indicated by A? Quadrate lobe of the liver

What is indicated by B? Pancreas



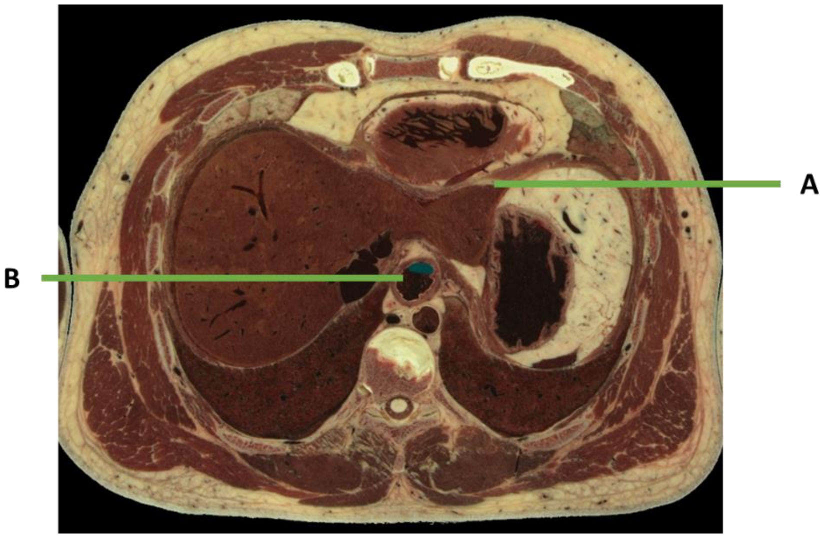
What is indicated by A? Spleen



Identify what is indicated by A? Azygos vein

Identify what is indicated by A? Stomach

Identify what is indicated by B? Right crus of the Diaphragm



Identify what is indicated by A? Diaphragm

Identify what is indicated by B? oesophagus

Identify what is indicated by A? superficial fascia (camper's- fatty layer)

Identify what is indicated by B? Right lung

Thanks for Participating and we do appreciate your effort…

Participant consent and use of data

We have developed this test in order to obtain Newcastle University student perceptions regarding the use of SECTRA in anatomy learning. The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the test items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name. By submitting this test, you are consenting for your data to be used for research purposes. Do not submit the test if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan (iain.keenan@newcastle.ac.uk)

Abdullah Ben awadh (a.ben-awadh2@newcastle.ac.uk)

Appendix M (2D learning activity Post-test)

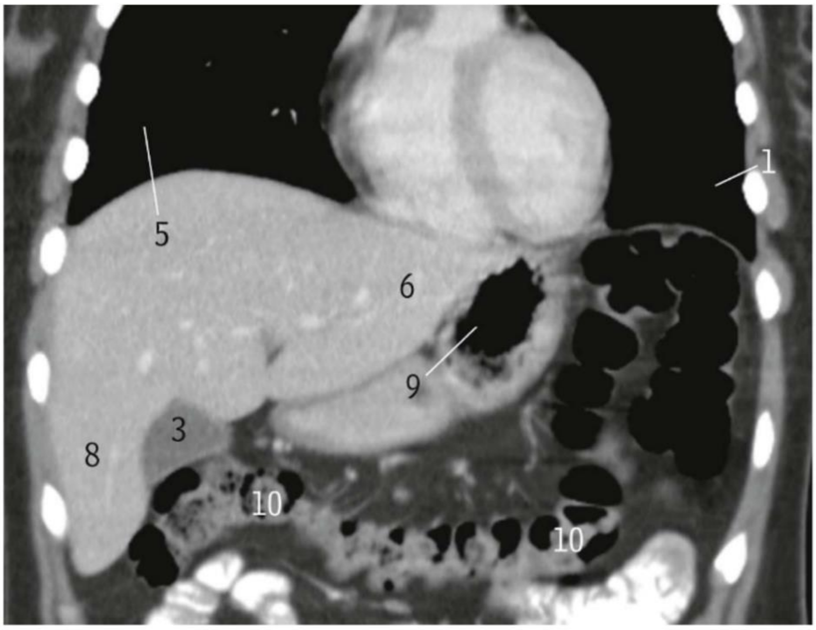
Post-test Clinical imaging questions:

Name: _________________________________

Student ID number (Participation number): ___________________________

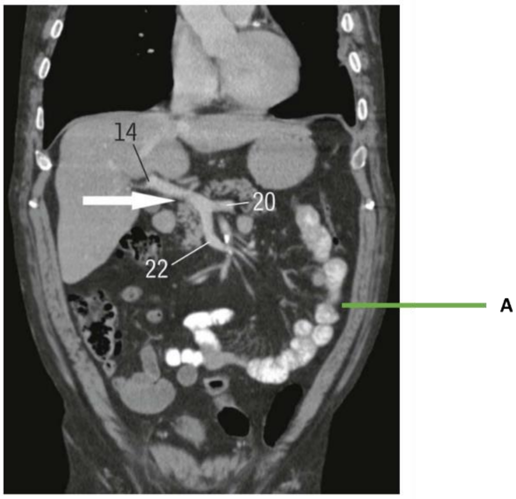
LEARNING OUTCOME: Describe and identify the abdominal viscera

The test includes 12 identification questions with one or two questions under each image.

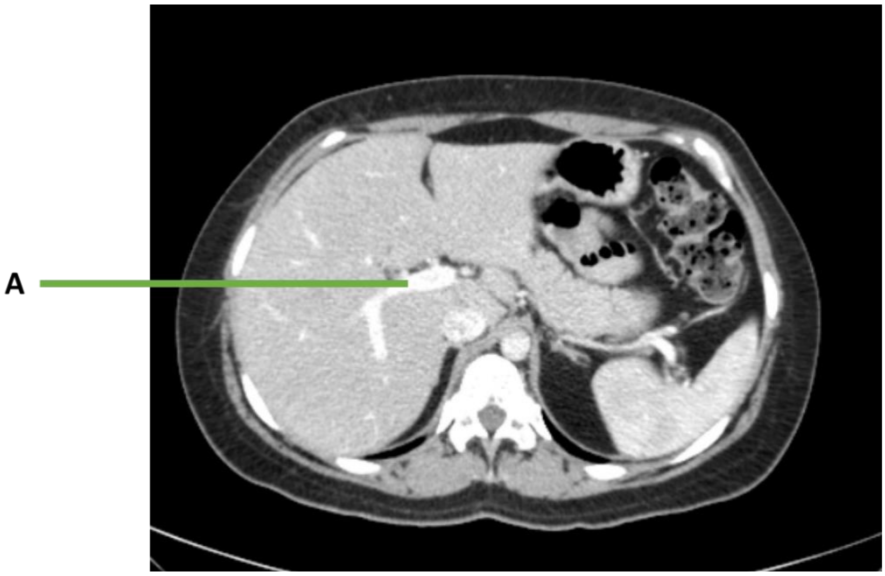


What is indicated by 3? Gallbladder

What is indicated by 6? Left lobe of the Liver

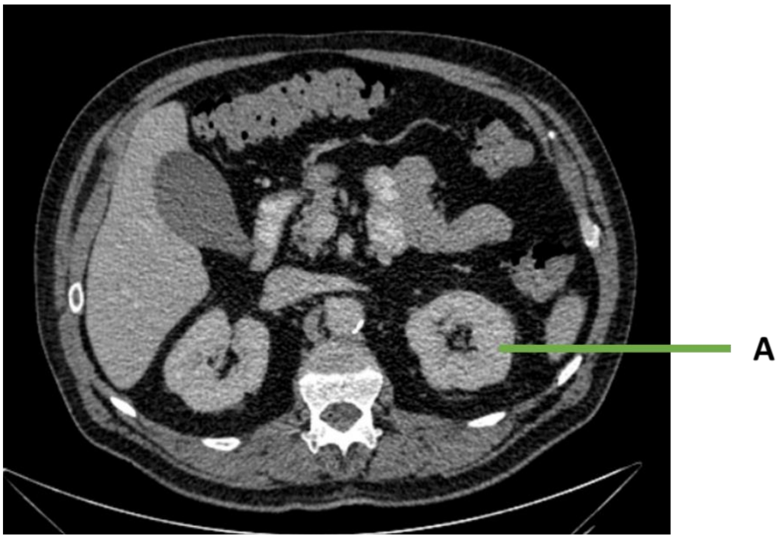


What is indicated by A? Descending colon



What is indicated by A? Portal vein

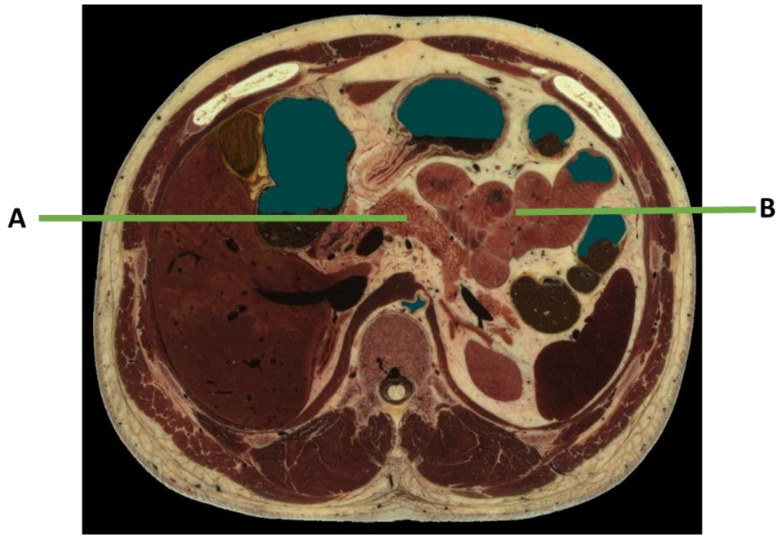
What vein is indicated by A? Inferior Vena Cava



What is indicated by A? Left Kidney

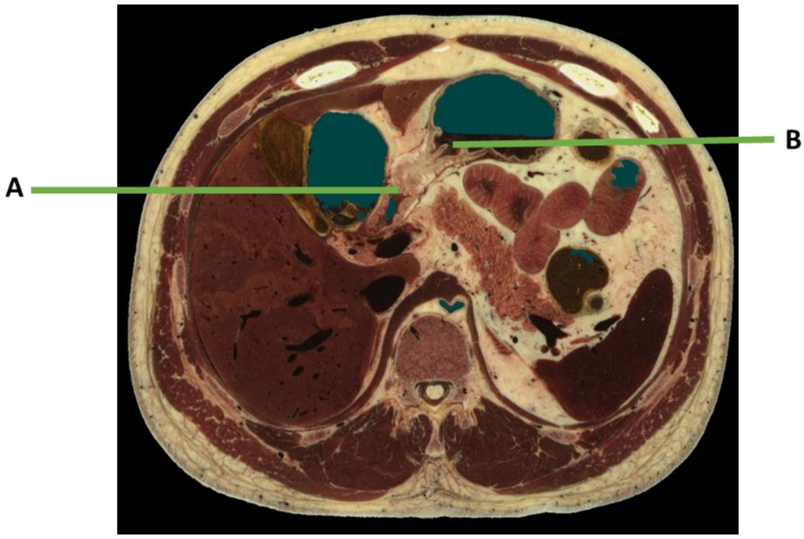
Identify what is indicated by A? oesophagus

What is indicated by B? Aorta



What is indicated by A? Small intestine

Identify what is indicated by B? Pancreas



Identify what is indicated by A? Duodenum

Identify what is indicated by B? Pyloric orifice

Thanks for Participating and we do appreciate your effort…

Participant consent and use of data

We have developed this test in order to obtain Newcastle University student perceptions regarding the use of SECTRA in anatomy learning. The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the test items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name. By submitting this test, you are consenting for your data to be used for research purposes. Do not submit the test if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan (iain.keenan@newcastle.ac.uk)

Abdullah Ben awadh (a.ben-awadh2@newcastle.ac.uk)

Appendix N (Sectra Education Portal Usage Questionnaire)

Sectra Education Portal Usage Questionnaire

Thank you for taking the time to complete this questionnaire, your participation is very much appreciated.

Name:

Student ID number (Participation number):

Please read and respond to each question carefully

I- Demographics

Gender

☐ Male | ☐ Female | ☐ Other | ☐ Prefer not to say

Age

☐ (17-20) | ☐ (21-24) | ☐ (25-30) | ☐ (30-35) | ☐ (35+)

Highest previous qualification

☐ (Further Education – e.g. A-levels) | ☐ (Bachelor Degree) | ☐ (Master Degree) | ☐ (PhD)

Do you have any previous experience of learning anatomy other than during your current degree? If yes please provide more details.

☐ No | ☐ Yes

Do you have any previous work experience relating to anatomy and/or clinical imaging? If yes please provide more details.

☐ No | ☐ Yes

A- Did you use the Sectra Education Portal to complete any of the activities in the CASE 3 Sectra Education Portal GUIDE: 'ANATOMY OF THE ABDOMINAL VISCERA'?

☐ Yes ☐ NO

If you answered 'yes' please continue to Part II, B below

If you answered 'no', please state the reasons why you did not access the Sectra Education Portal

----

B- Which activities in the CASE 3 Sectra Education Portal GUIDE: 'ANATOMY OF THE ABDOMINAL VISCERA' did you complete?

PART ONE: THREE-DIMENSIONAL IMAGING OF THE ABDOMEN ☐

PART TWO: CROSS-SECTIONAL IMAGING OF THE ABDOMEN ☐

BOTH PARTS ONE AND TWO ☐

C- What other resources (if any) did you use with the Sectra Education Portal in order to complete any part of the CASE 3 Sectra Education Portal GUIDE: 'ANATOMY OF THE ABDOMINAL VISCERA'?

D- How many times did you access the Sectra Education Portal since 12th November 2019?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ Other:

E- Approximately, how many minutes did you spend on the Sectra Education Portal on each occasion that you accessed it since 12th November 2019?

☐ 0-10min ☐ 10-30min ☐ 31-60min ☐ 61-120min ☐ 121min-180min ☐ Other:

F- Approximately, how many minutes did you spend on the Sectra Education Portal in total since 12th November 2019?

☐ 0-10min ☐ 10-30min ☐ 31-60min ☐ 61-120min ☐ 121min-180min ☐ Other:

G- On which device(s) did you access the Sectra Education Portal (select all that apply).

☐ Android phone ☐ iPhone ☐ Windows Tablet ☐ iPad ☐ Laptop PC ☐ Desktop PC
☐ iMac ☐ Other (please specify): …………………

Did any of the device(s) on which you accessed the Sectra Education Portal have a touch screen?

☐ Yes ☐ No

II. Sectra Education Portal Usage

From question 1 to question 11 Please tick the most appropriate answer for each question, where 1 is Strongly Disagree and 7 is Strongly Agree.

1- The Sectra Education Portal improved my understanding of 3D gross anatomy of the abdomen.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

2- The Sectra Education Portal improved my understanding of the gross anatomy of the abdomen in cross-sectional images.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

3- The ability to actively interact with and manipulate Sectra Education Portal images was important for improving my interpretation of 3D anatomical features in cross-sectional images.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

4- Using 3D printed anatomical models with the Sectra Education Portal would further enhance my learning

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

5- Please describe why your interactions with the Sectra Education Portal were/were not important in improving your understanding of 3D and cross-sectional anatomical features.

6- If you used touch screen device(s) with the Sectra Education Portal, please describe why this was/was not important in improving your understanding of anatomical features in 3D images and cross-sections.

7- Please describe any OTHER resources you used with the Sectra Education Portal in order to complete any part of the CASE 3 Sectra Education Portal GUIDE: 'ANATOMY OF THE ABDOMINAL VISCERA'?

8- Please describe any self-directed anatomy and clinical imaging resources (other than the Sectra Education Portal) that you currently/previously used in your own time for study or revision (outside of timetabled teaching).

Anatomy resources:

Imaging resources:

9- The Sectra Education Portal is a valuable self-directed learning resource for studying 3D and cross-sectional anatomy and I wish to use the Sectra Education Portal for studying anatomy again in the future.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

10- I would recommend the Sectra Education Portal to other medical students for their anatomy learning

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

11- We plan to increase the number of available logins for the Sectra Education Portal in the near future. Please describe any other suggestions you may have for improving how we use the Sectra Education Portal.

If you would like to participate in a focus group discussion about the Sectra Education Portal, please provide your email address below. A Newcastle University Certificate of Appreciation signed by Dr Keenan will be awarded to all focus group participants and a free lunch will also be provided.

Email: ____

Many thanks for your participation.

We are very grateful for the time and effort you have contributed to participating in our study.

Participant consent and use of data

We have developed this questionnaire in order to obtain Newcastle University student perceptions regarding the most challenging topics in anatomy learning and regarding the use of Sectra Education Portal and 3DP models in anatomy learning.

The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the questionnaire items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name.

By submitting this questionnaire, you are consenting for your data to be used for research purposes. Do not submit the questionnaire if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan iain.keenan@newcastle.ac.uk

Abdullah Ben awadh a.ben-awadh2@newcastle.ac.uk

Appendix O (Sectra Education Portal tutorial guide)

MBBS CASE 3 Sectra Education Portal GUIDE

ANATOMY OF THE ABDOMINAL VISCERA

YOU SHOULD USE THIS GUIDE TO SUPPORT YOUR STUDY OF THE FOLLOWING CASE 3 LEARNING OUTCOMES USING THE SECTRA EDUCATION PORTAL:

Identify the peritoneal cavity and its compartments and the major abdominal organs contained within it

Describe and identify the gross anatomical features of the kidney and urinary tract in females and males

Describe and identify the structure and relations of the viscera, nerves and vessels that are associated with the posterior abdominal wall

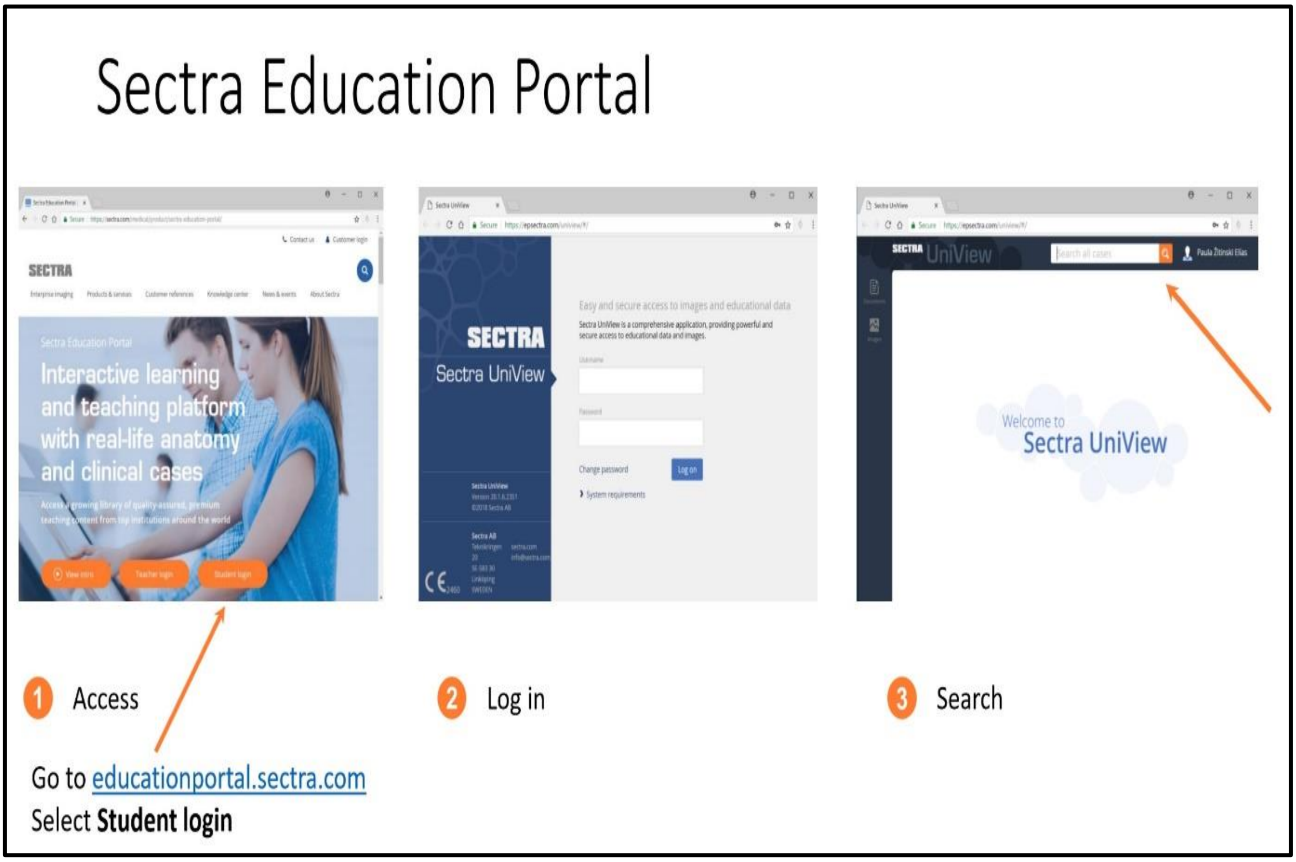
Access the Sectra Education Portal (SEP) here:

https://medical.sectra.com/product/sectra-education-portal/

Note: It is important that you use the correct browser for your device:

Use Microsoft Edge or Google Chrome (Windows) or Safari (iPad, Mac).

Use the provided user and password to access SEP through the student login icon.



Each patient case in SEP is allocated a specific code number

Once logged in you can access individual SEP cases by searching for the code number

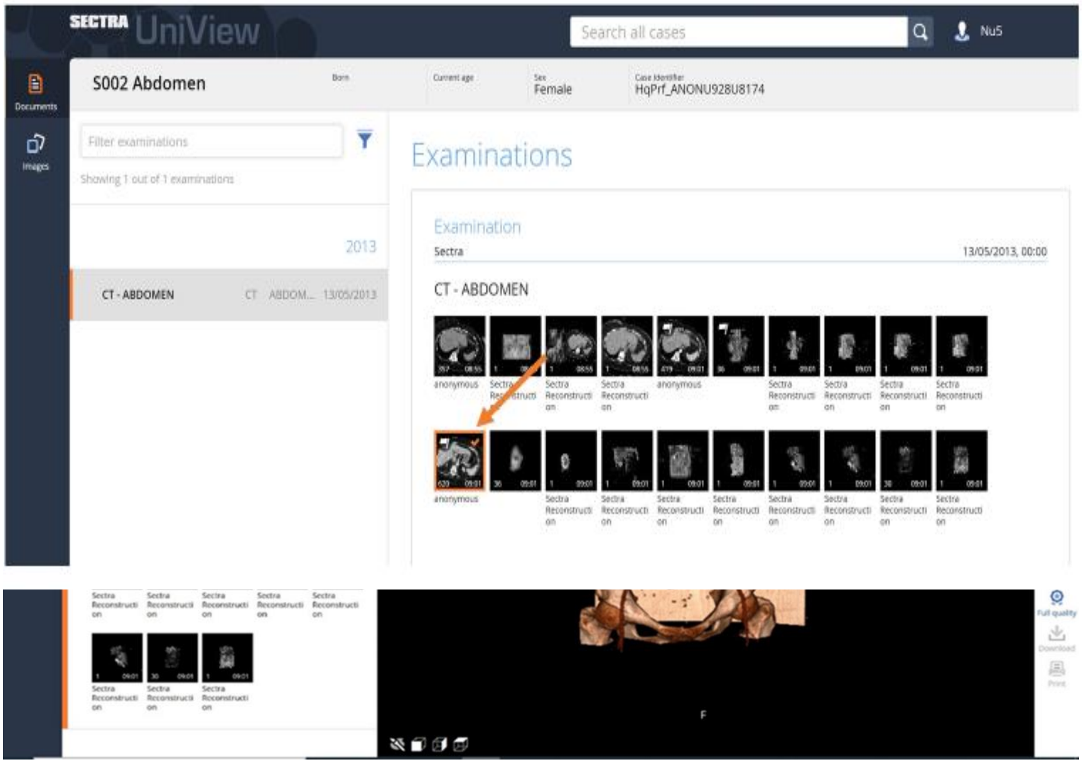
In this activity you will need to access cases with codes S002, S051, S060, S085, S087

You can also search for anatomical regions using keywords e.g. 'abdomen'

PART ONE: THREE-DIMENSIONAL IMAGING OF THE ABDOMEN

Search for S002 and you will see all CT scans for this case.

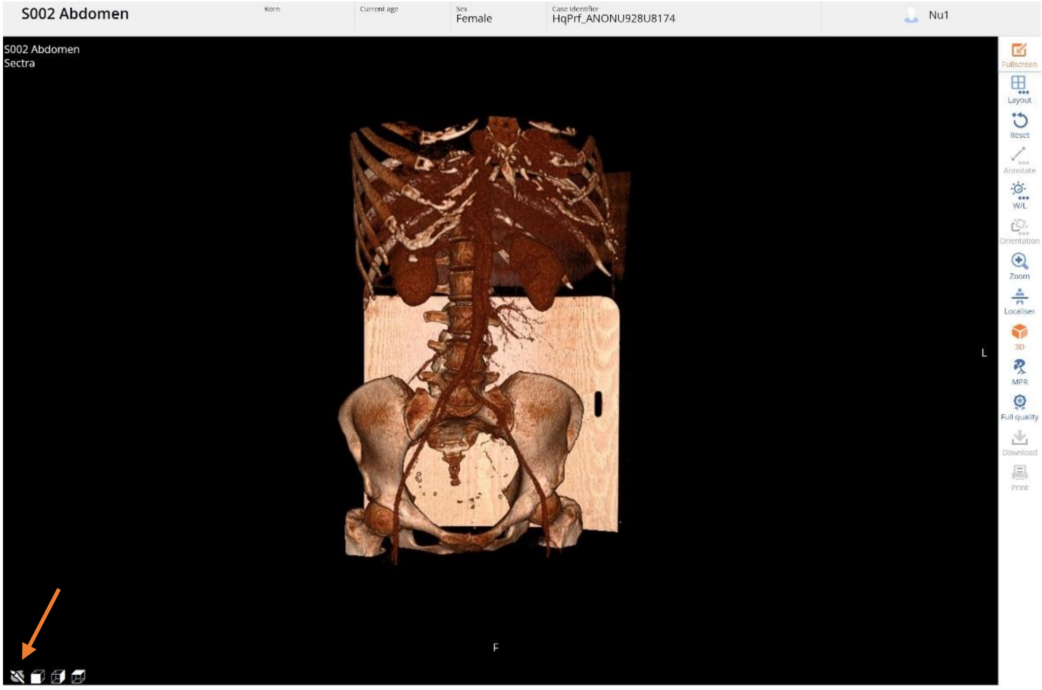
Select the thumbnail (highlighted in image below) and the CT stack will open.

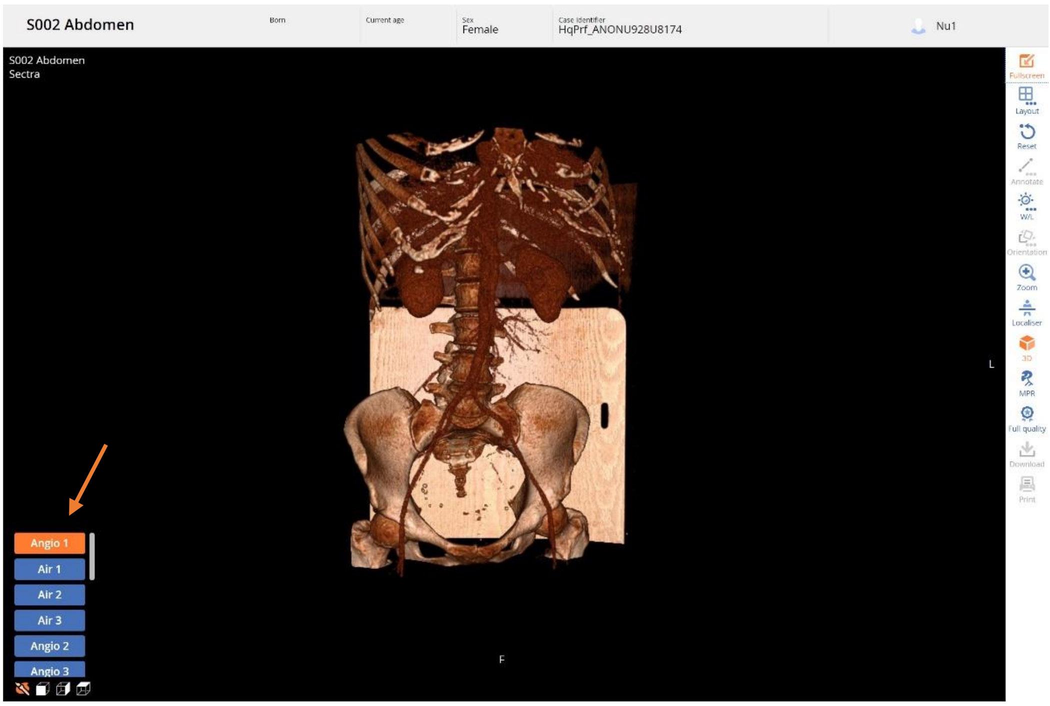


Now select the 3D option (highlighted in the image below) to produce a 3D image of the abdominal contents.

By selecting the 3D option, you will generate a 3D digital model that now you can rotate and manipulate for your 3D understanding of the abdominal region.

Check all bookmarks when you use the 3D render option by pressing on the first icon down on the left corner (highlighted in the image below).





Activity 1: Identify the following features of the abdominal cavity in the 3D rendered image and label them on the images provided below. You may need to use text books or other resources to help you.

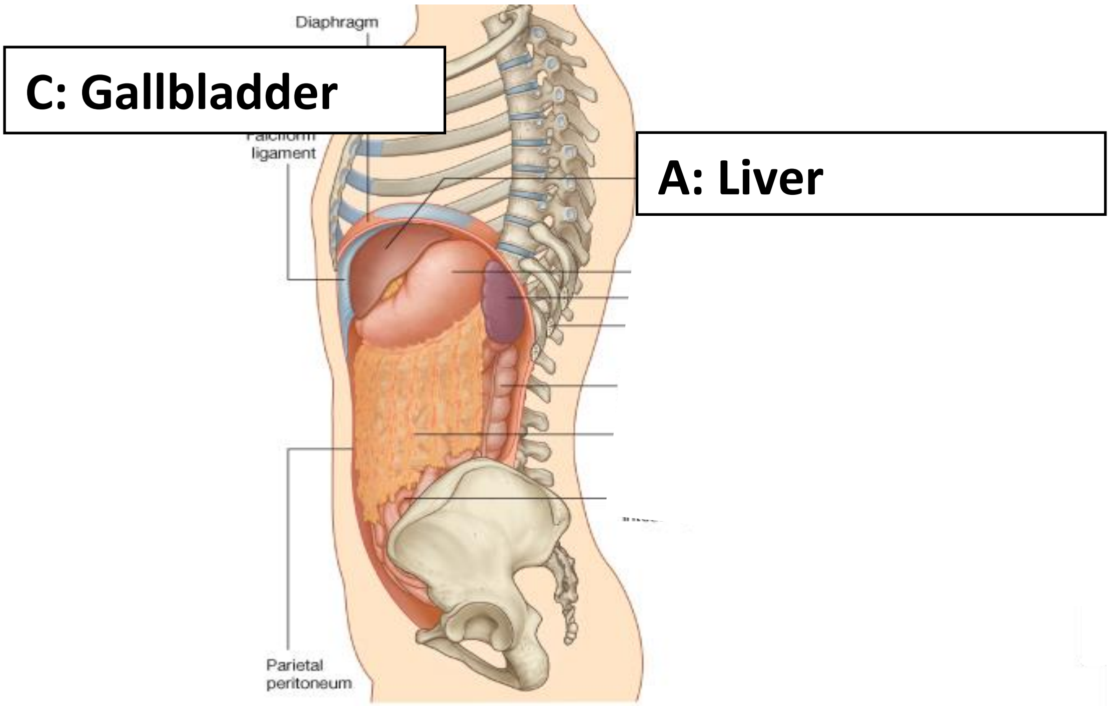
Right lobe of liver, left lobe of liver, gallbladder

Abdominal aorta, coeliac trunk

Right and left kidneys, pancreas, spleen

Small intestine

CODE	Features
S002	Liver and associated vessels
S051	Inferior vena cava
S060	Branches of coeliac trunk, SMA, IMA
S085	Liver and hepatic portal system
S087	Liver and associated vessels



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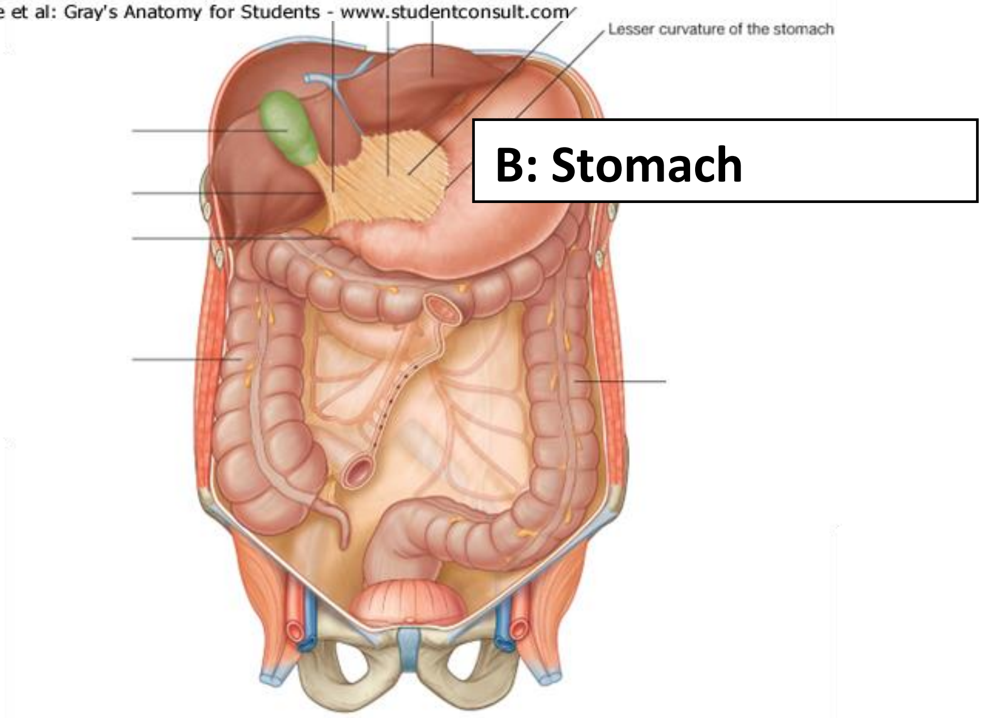

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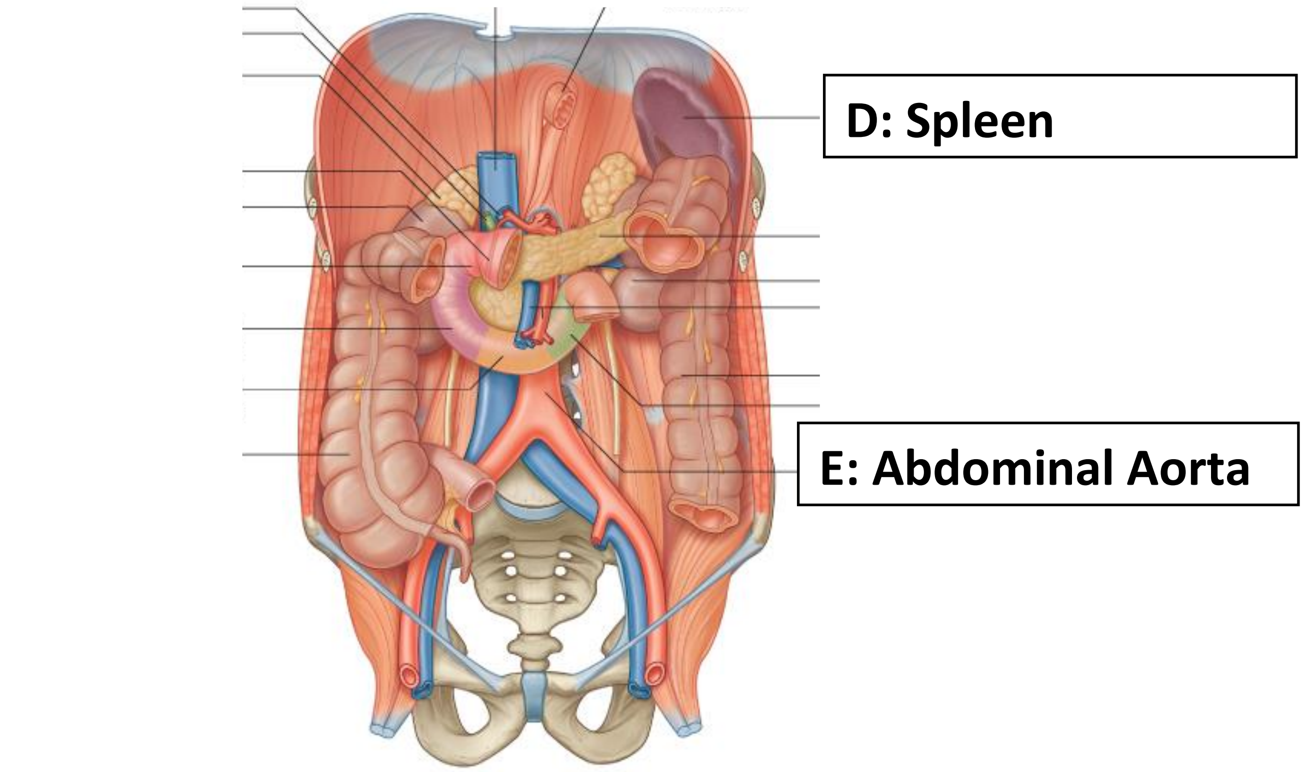
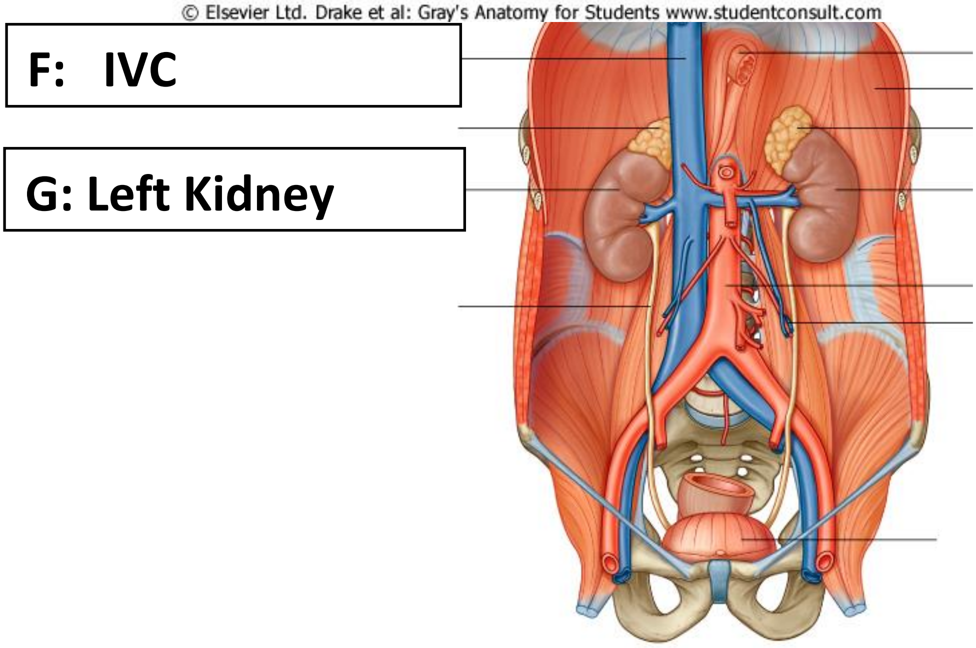


D: Spleen
E: Abdominal Aorta

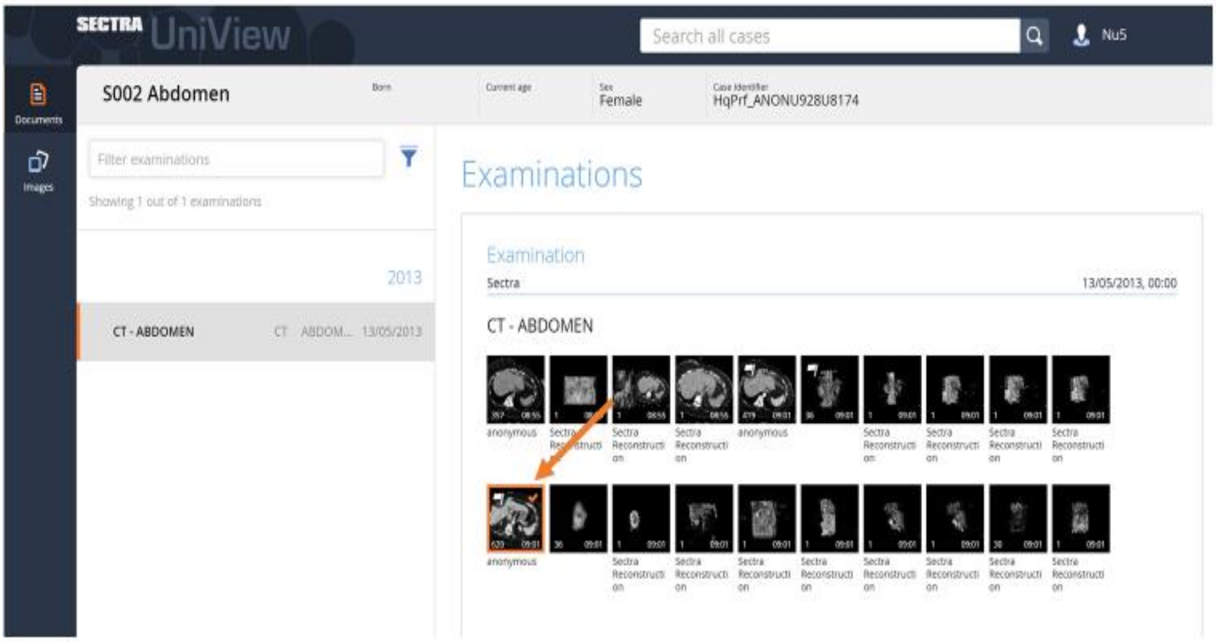


F: IVC
G: Left Kidney

PART TWO: CROSS-SECTIONAL IMAGING OF THE ABDOMEN

Once you access case S002 you will see all CT scans for this case.

Select the thumbnail (highlighted in image below) and the CT stack will open.



You will then see the toolbar on the left side of the screen (see image below).

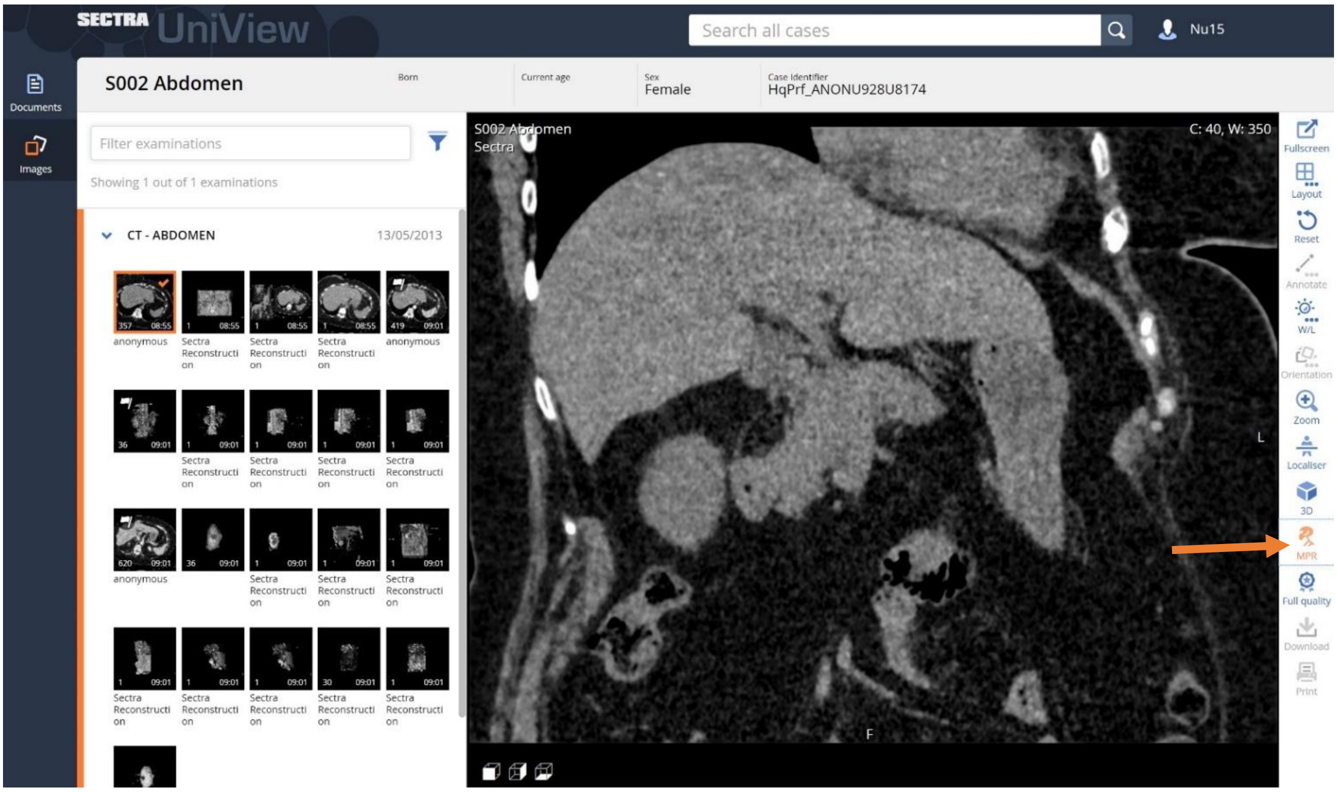
Now select the CT scan and scroll up and down by moving the middle button on your mouse (if you have one).

On the bottom of the screen you can use the circular icon (highlighted in image below) to scroll up and down the CT scan if you don't have middle button on your mouse.

Note: If you are using a touch screen device, please refer to the following instructions:

- Use one finger to scroll up and down (from superior to inferior within the CT stack)
- Use two fingers to pinch and zoom (increase or decrease the magnification)

For Coronal view select the icon MPR from the tool bar on the left (see image below).



Access all the following cases from the list below.

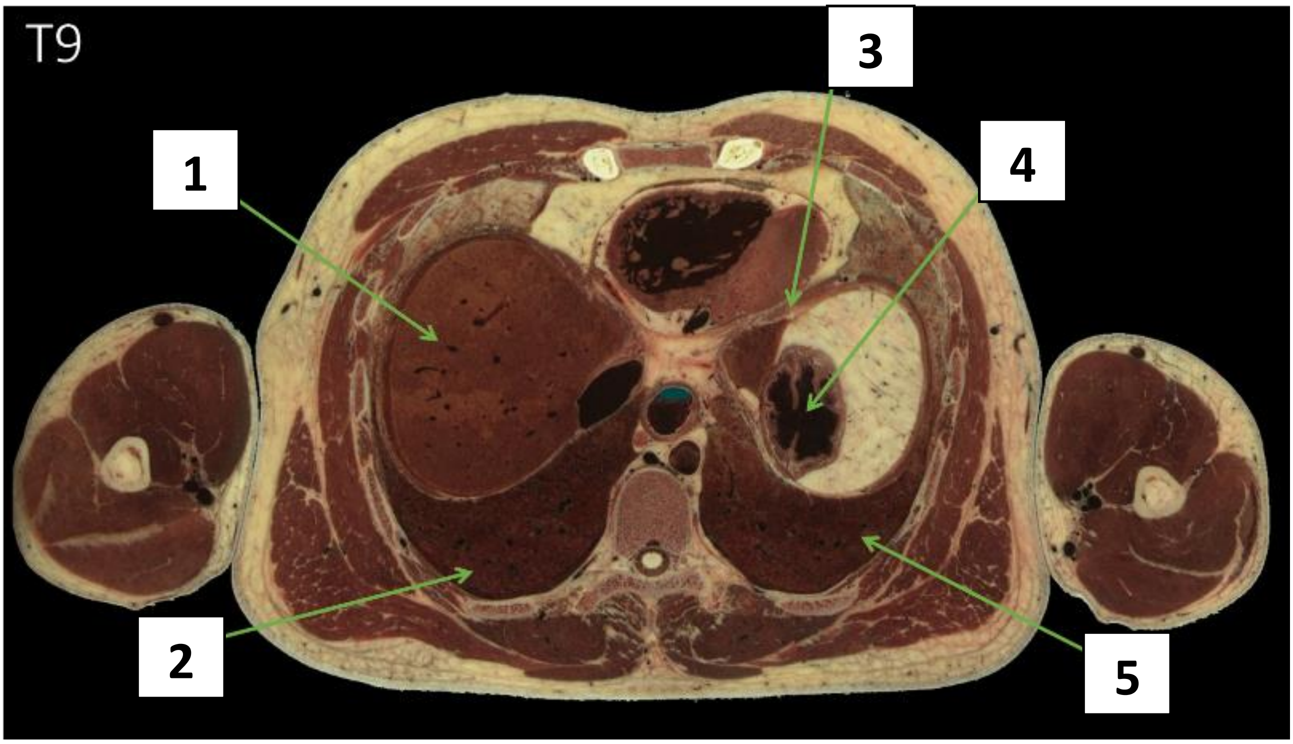
As you scroll up and down identify the provided abdominal region from the list below:

- Right lobe of liver, left lobe of liver, gallbladder
- Inferior vena cava, hepatic veins, portal vein, abdominal aorta
- Oesophagus, stomach, pylorus, duodenum.
- Jejunum, ileum, ascending, transverse and descending colon
- Right and left kidneys, pancreas, spleen
- Dome of diaphragm, left and right crura of diaphragm.

CODE	Features
S002	Access the CT scan with the 620 slides Liver and associated vessels
S051	Inferior vena cava
S060	Branches of coeliac trunk, SMA, IMA
S085	Liver and portal system
S087	Liver and associated vessels

Activity 2: Identify the following features of the abdominal cavity in cross sectional CT scans using the SEP and then identify and label them on the cross-sectional images provided below

- Right lobe of liver, left lobe of liver, gallbladder
- Inferior vena cava, hepatic veins, portal vein, abdominal aorta
- Oesophagus, stomach, pylorus, duodenum.
- Jejunum, ileum, ascending, transverse and descending colon
- Right and left kidneys, pancreas, spleen
- Dome of diaphragm, left and right crura of diaphragm.



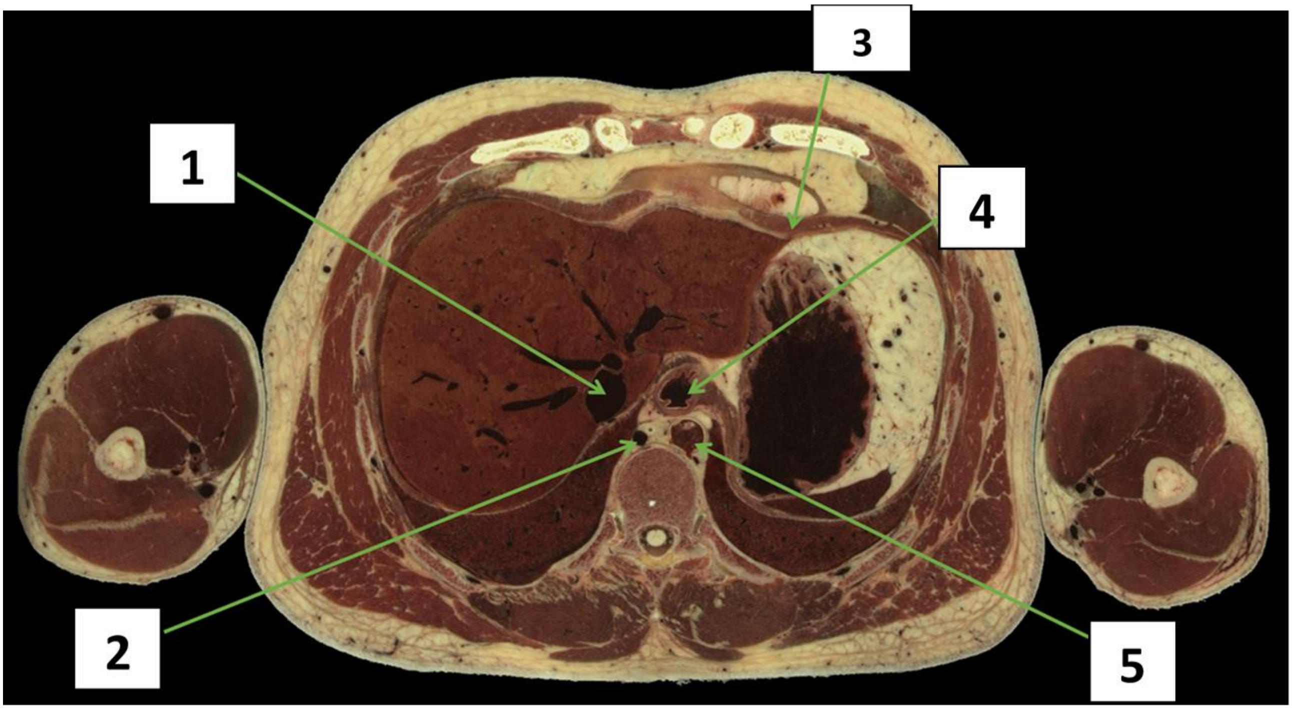
1. Liver

2. Right Lung

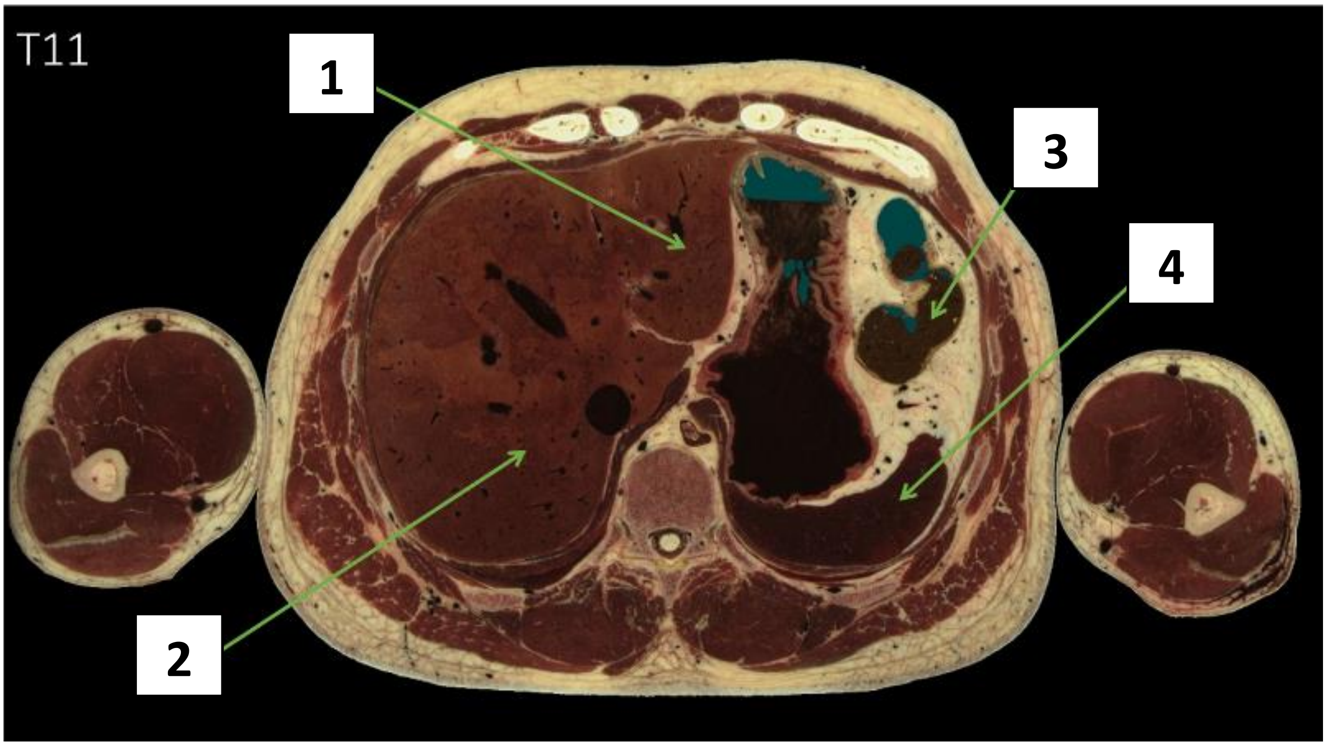
3. Diaphragm

4. Stomach

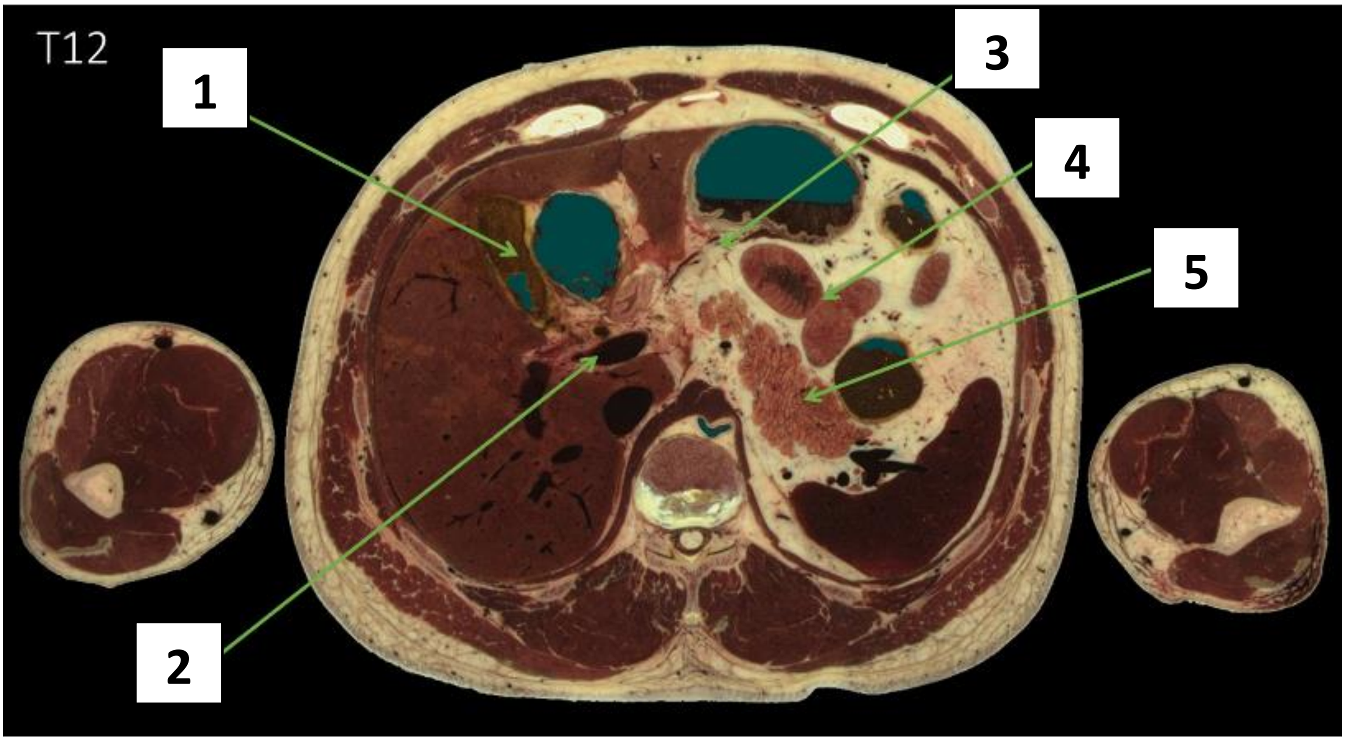
5. Left Lung



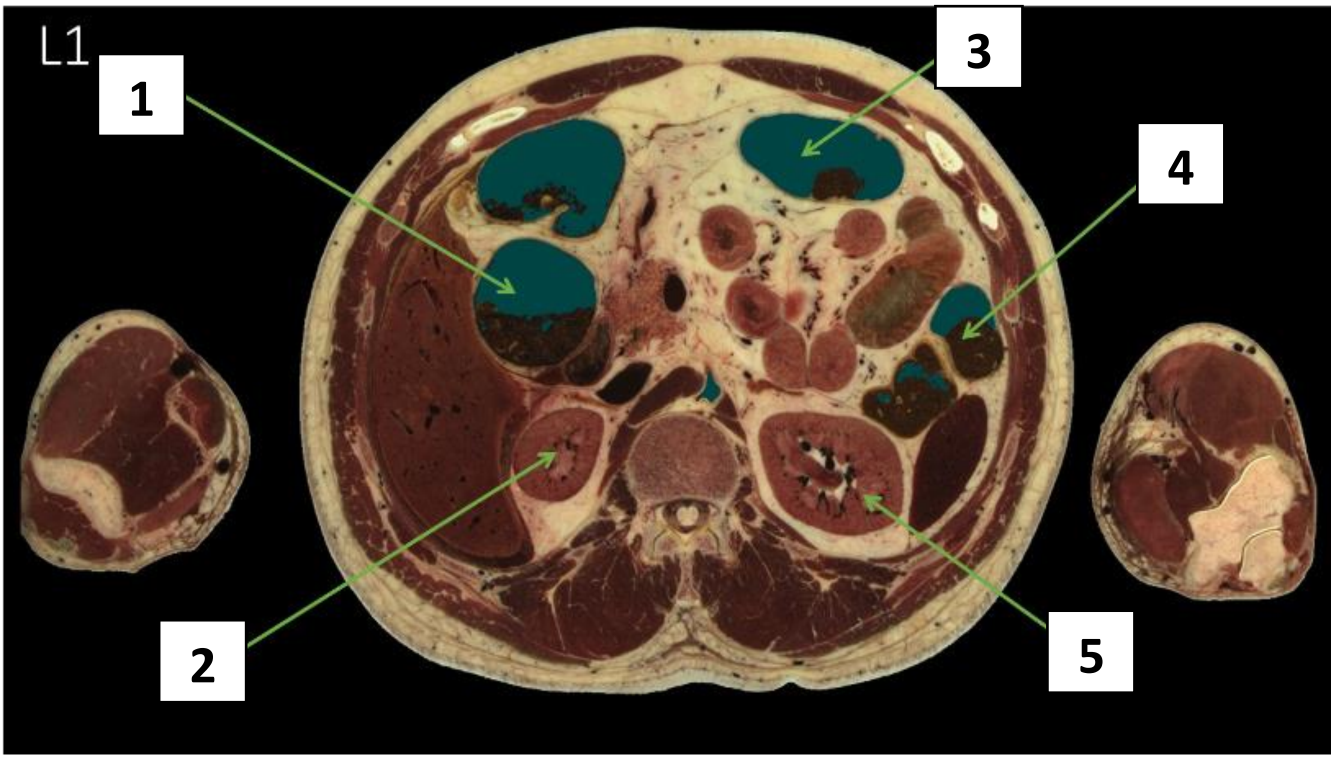
1. Inferior Vena Cava
2. Azygos vein
3. Diaphragm
4. Oesophagus
5. Aorta



1. Liver Left lobe
2. Liver Right lobe
3. Descending colon
4. Spleen



1. Gallbladder
2. Hepatic Portal Vein
3. Pyloric orifice
4. Small intestine (Jejunum)
5. Pancreas



1. Ascending colon
2. Right kidney
3. Transverse colon
4. Descending colon
5. Left kidney

Appendix P (Digital Embryology Resources Tutorial Guide)

MBBS CASE 2 Digital Embryology Resources

Embryology of the Heart

YOU SHOULD USE THIS GUIDE TO SUPPORT YOUR STUDY OF THE FOLLOWING CASE 2 LEARNING OUTCOME:

Describe the embryological development of the heart and great vessels

IMPORTANT: Before you begin the activities in this guide, you should ensure that you have viewed these resources on the MLE:

Case 2 embryology lecture slides

Case 2 embryology lecture ReCap

Case 2 embryology timeline slide

These embryology animations:

https://anat550.sitehost.iu.edu/cvanim/index.html

This guide will support you in understanding of gastrointestinal embryology through use of the Human Development Biology Resource (HDBR) Atlas http://hdbratlas.org/

There are FOUR sections to complete in this guide:

PART 1: UNDERSTANDING THE DEVELOPMENT OF THE HEART FROM CS12 TO CS23

PART 2: INTRACTIVE THREE-DIMENSIONAL MODELS OF THE HEART

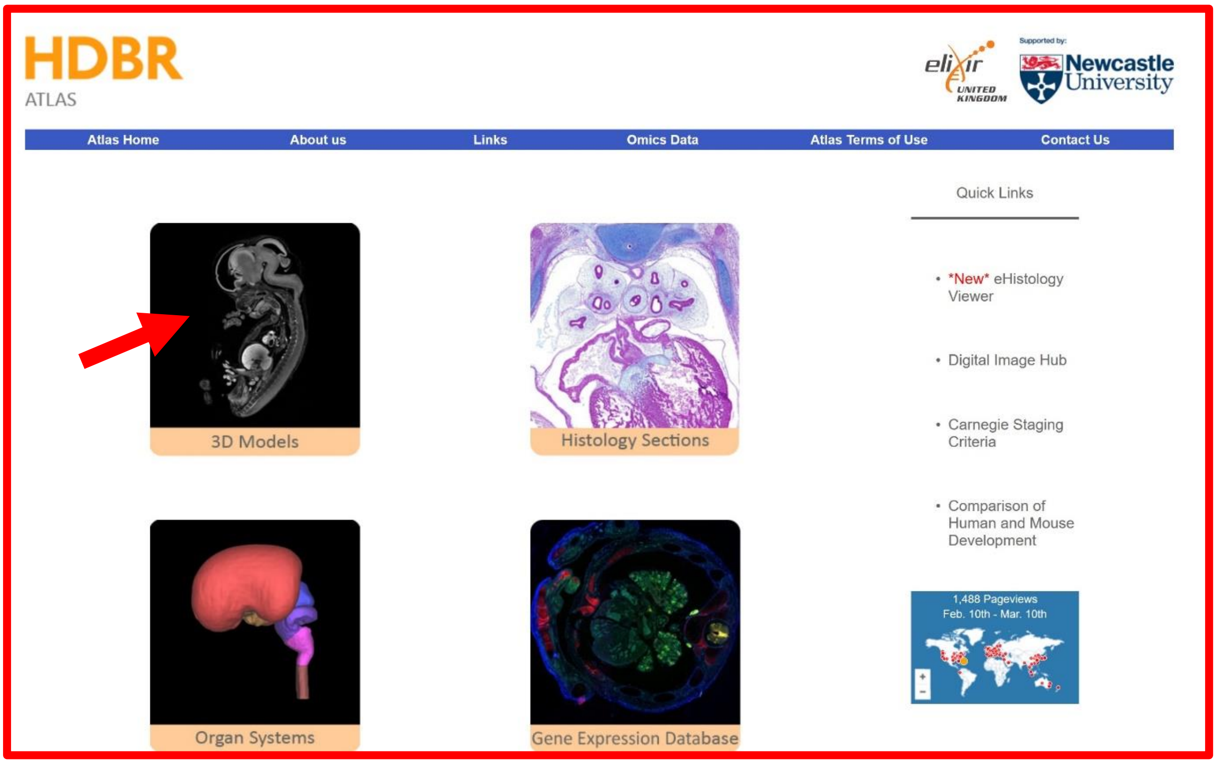
PART 3: SPOTTER ACTIVITY

PART 4: SPOTTER ANSWERS

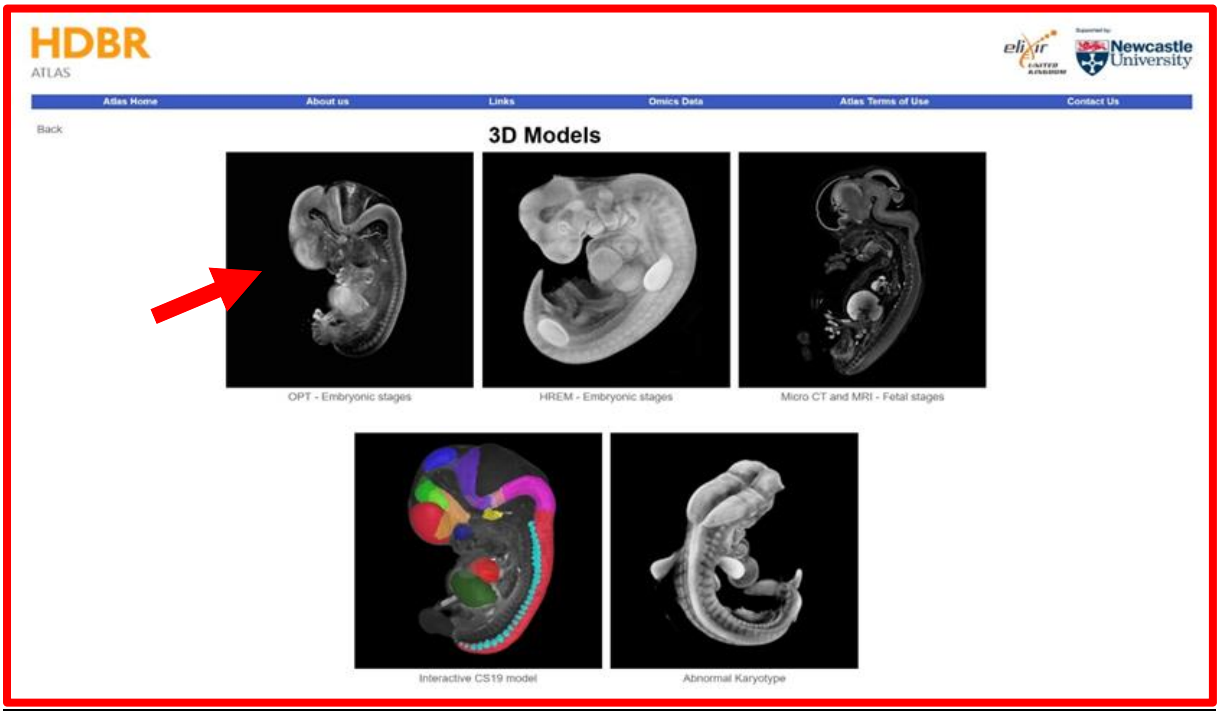
Feedback: We would appreciate your views on the activities in this guide and the HDBR resource. Once you have completed this guide, please complete the questionnaire by accessing the link provided at the end of this guide

PART 1: UNDERSTANDING THE DEVELOPMENT OF THE HEART FROM Weeks 4-8 of development

On the HDBR home page http://hdbratlas.org/ select the 3D Models icon.

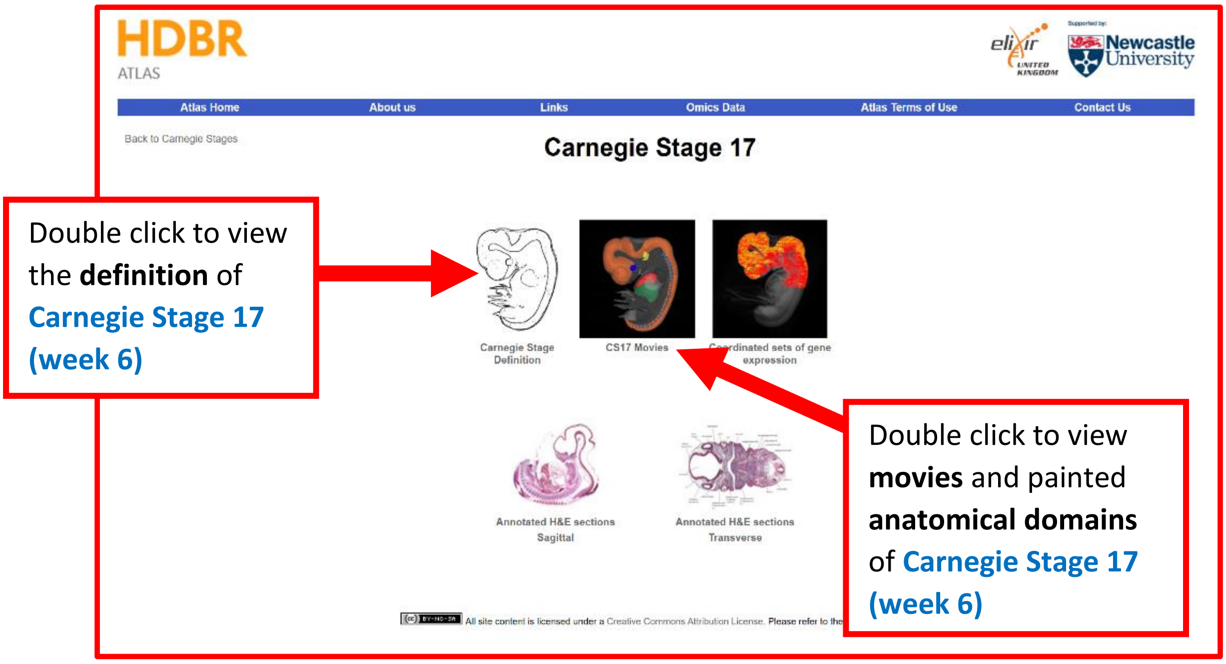


Double click on the icon in the image below to access the definition of the Carnegie stages of embryonic development. Human development can be classified by Carnegie Stages (CS) as well as by days and weeks of development



You will reach the page below, where you can view digital 3D embryo models at different Carnegie stages and the definition of each stage. For example, CS 17 is week 6.

You will see the page below:

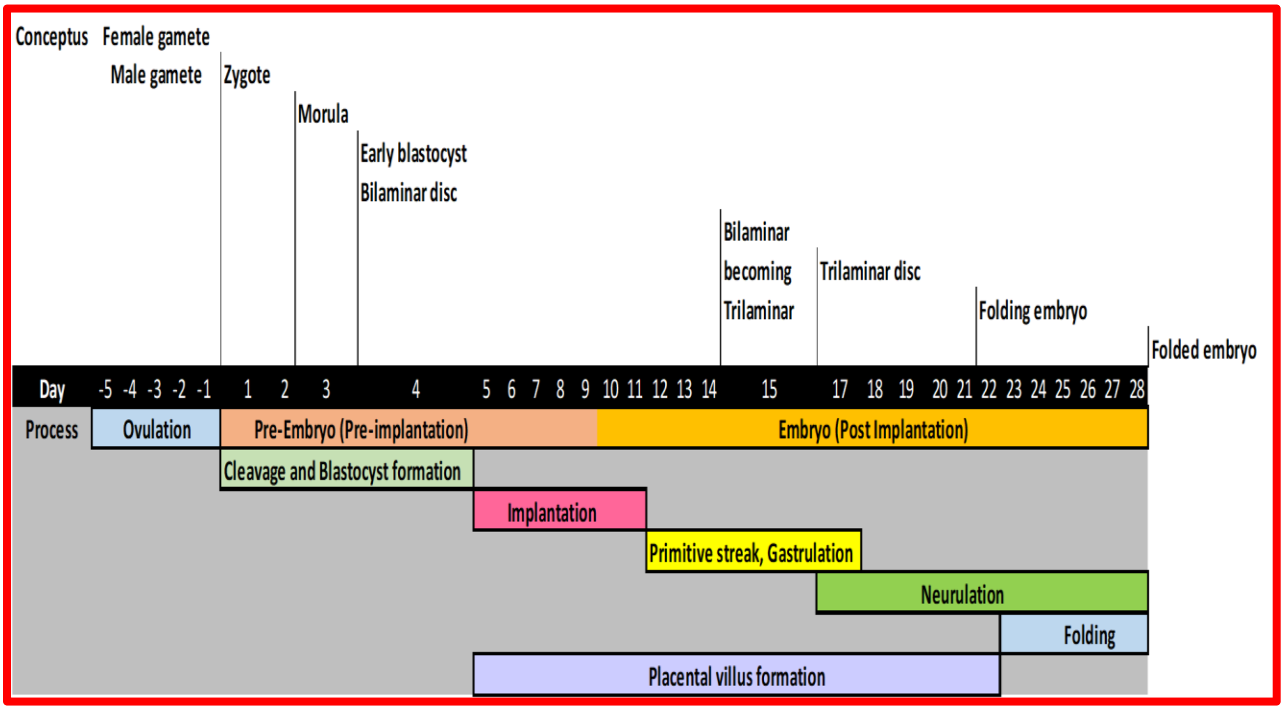


You can then repeat these steps for all of the available Carnegie stages.

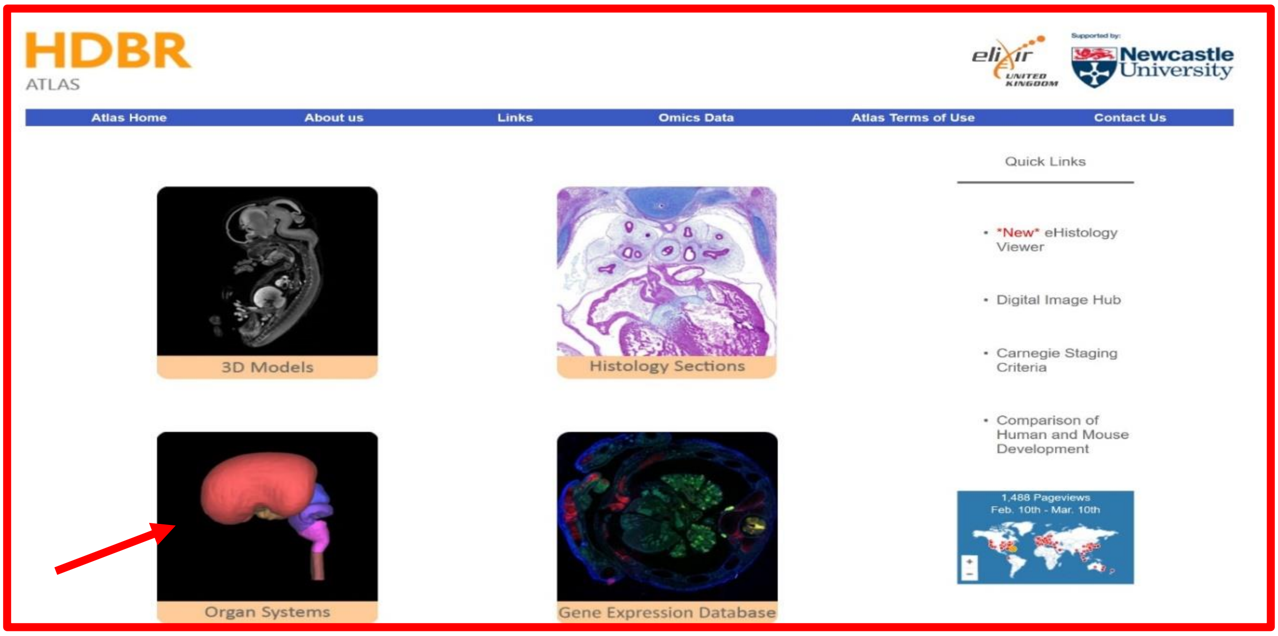
You can find more information about Carnegie stages here:
https://embryology.med.unsw.edu.au/embryology/index.php/Carnegie_Stages

PART 2: INTRACTIVE THREE-DIMENSIONAL MODELS OF THE HEART

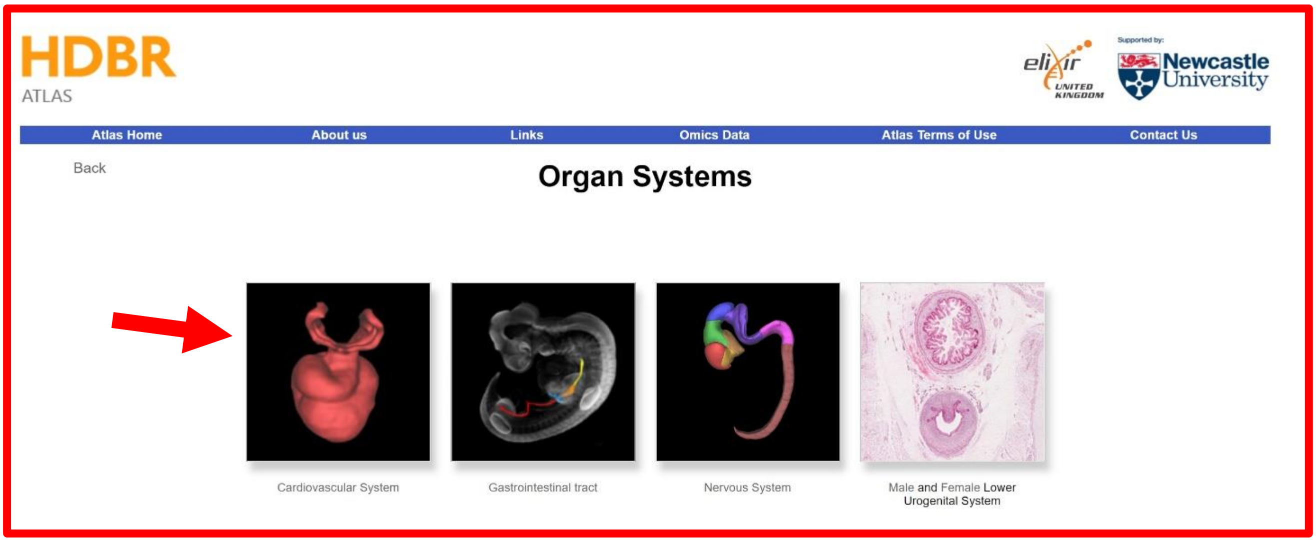
Now you are familiar with Carnegie stages, you should refer to the Case 2 embryology timeline (shown below and available as a slide on the MLE) and the Case 2 embryology lecture slides and ReCap (also available on the MLE).



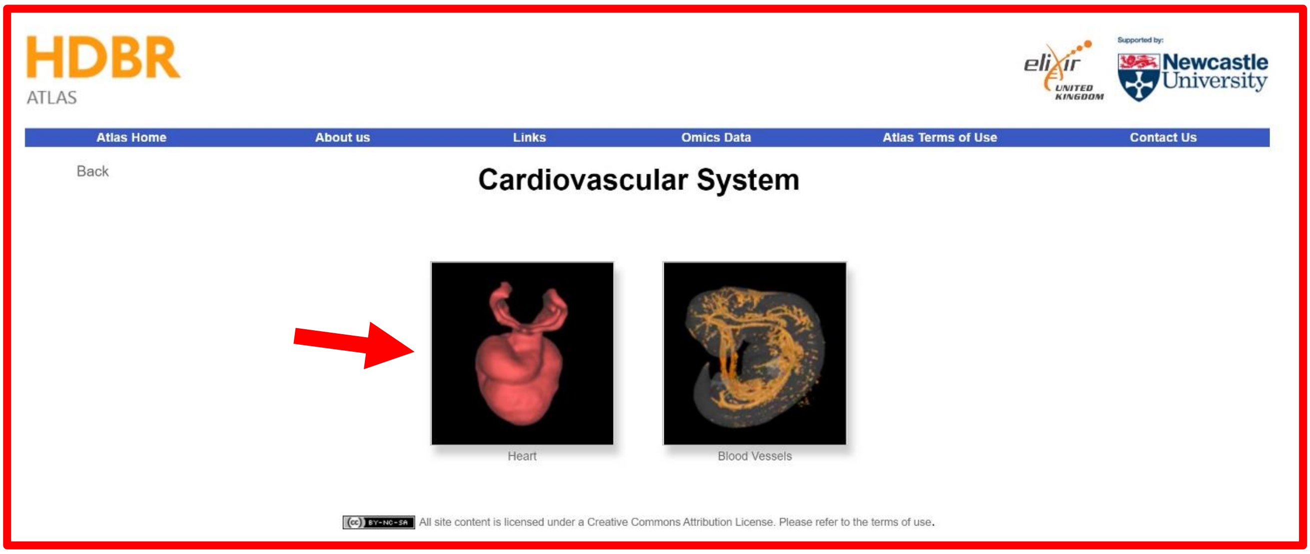
Now visit the HDBR website http://hdbratlas.org/ and select the Organ Systems icon below on the HDBR homepage:



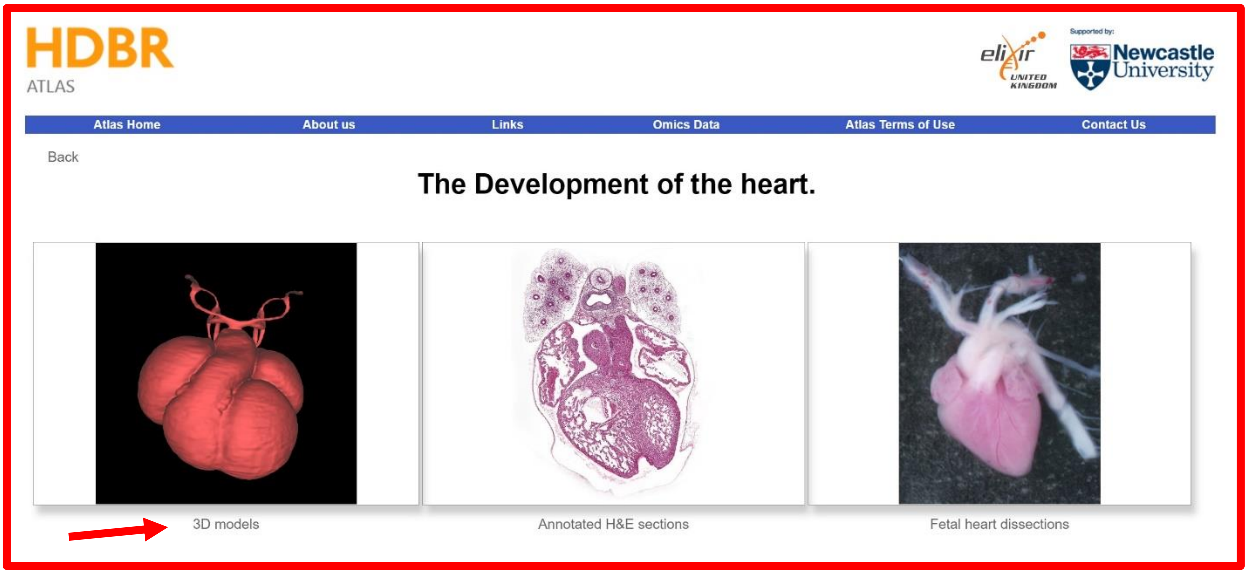
Various body systems are available, and for Case 2 we are looking at the Cardiovascular System. Double click on the icon shown below to select it.

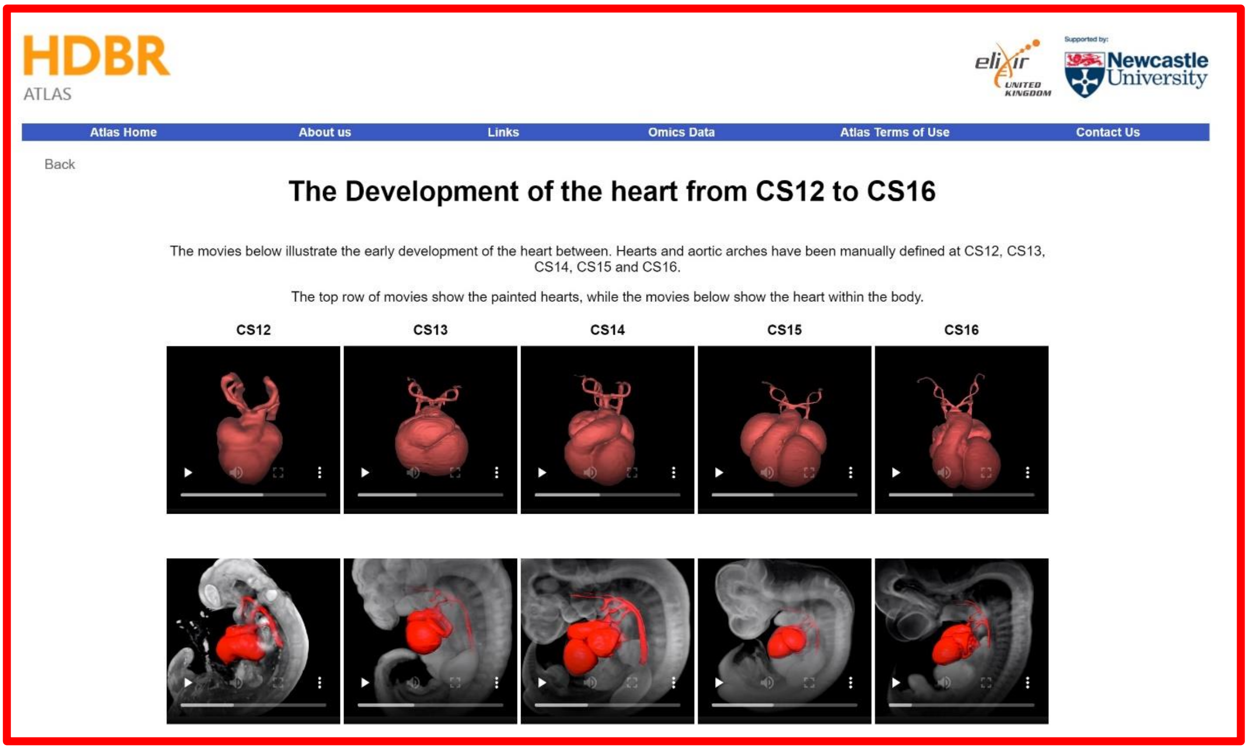


Having selected Cardiovascular System, you will be directed to the page below, and you should then select 3D Models of the Heart.



You will have now accessed the page shown below, with 3D digital models of the Cardiovascular System of the embryo at different Carnegie stages (CS).





The movies above illustrate the early development of the heart.

Hearts and aortic arches have been manually defined at CS12 (week 4), CS13 (week 4), CS14 (week 5), CS15 (week 5) and CS16 (week 6).

The top row of movies shows the painted hearts, while the movies below show the heart within the body.

You can view full screen videos with right click and select ‘open in new tab’.

You can download any video with right click and then select ‘download’.

Now follow the Information on the use of this interactive 3D-PDF models of the Embryo:

Technical Notes

This PDF file should be viewed in Adobe Acrobat Reader X or higher, available from http://www.adobe.com/downloads. 3D interaction is only possible on MS Windows or Mac OS. Javascript and playing of 3D content must be enabled.

Open *Edit* ⇨ *Preferences* to ensure the following:

1) In *3D & Multimedia*, enable *Enable playing of 3D content*
2) In *3D & Multimedia*, under *3D Tool Options*
   - for *Open Model Tree on 3D Activation* choose *Use Annotation's Settings*
   - for *Default Toolbar State* choose *Use Annotation's Settings*
   - disable *Show 3D Orientation Axis*
3) In *3D & Multimedia*, under *Auto-Degrade Options*
   - for *Optimalization Scheme for Low Framerate* select *None*
4) In *JavaScript*, under *JavaScript*
   - enable *Enable Acrobat JavaScript*

The PDF files are shown below

Carnegie stage 17 (42-44 days -Sectra).p	Carnegie stage 16 (37-42 days -Sectra).p	Carnegie stage 15 (35-38 days -Sectra).p	Carnegie stage 13 (28-32 days -Sectra).p	Carnegie stage 12 (26-30 days -Sectra).p
Carnegie stage 11 (23-26 days -Sectra).p	Carnegie stage 10 (21-23 days -Sectra).p	Carnegie stage 9 (19-21 days -Sectra).p	Carnegie stage 8 (17-19 days -Sectra).p	Carnegie stage 7 (15-17 days -Sectra).p
Carnegie stage 23 (56-60 days -Sectra).p	Carnegie stage 21 (53-54 days -Sectra).p	Carnegie stage 20 (51-53 days -Sectra).p	Carnegie stage 18 (44-48 days -Sectra).p	

After you open the PDF file with Adobe Acrobat Reader follow the information below

Selection of structures

The top left panel contains buttons to show or hide groups of structures, or to make them transparent.

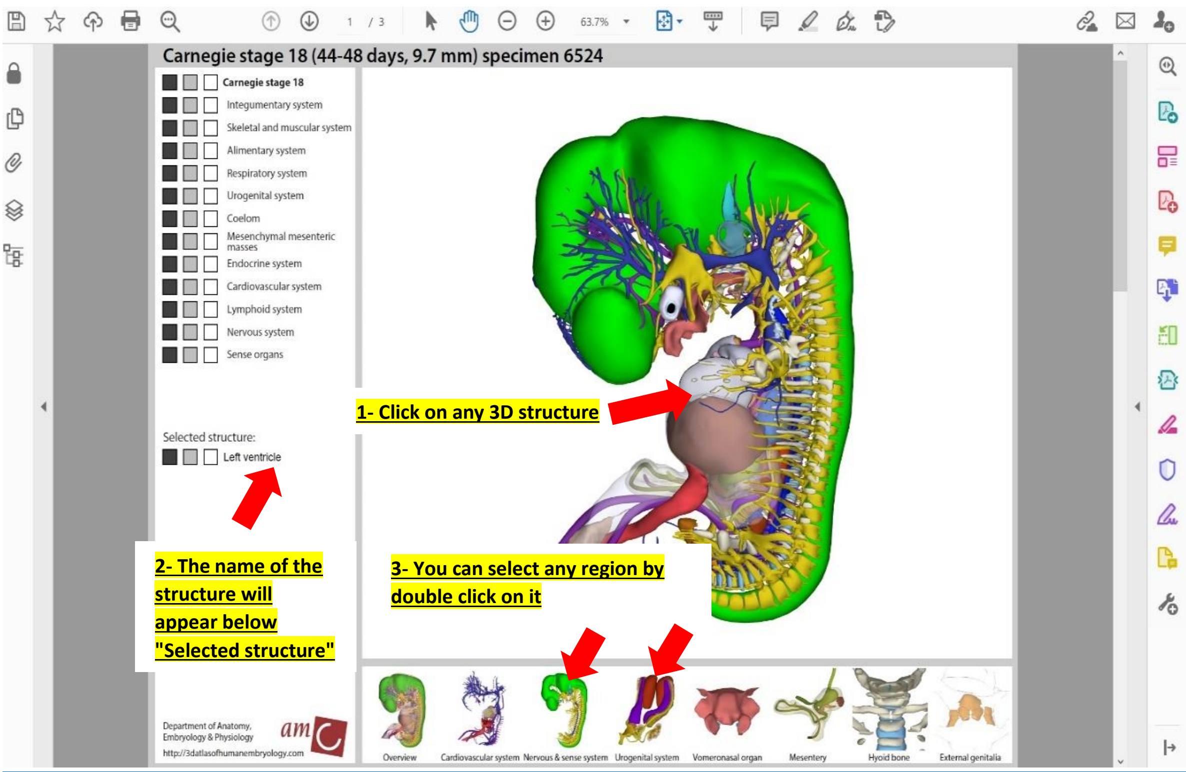
After a single click on a 3D structure, the structure will be highlighted, and the name of the structure will appear below "Selected structure".

Note that this function is disabled in Cross Section views (sct.).

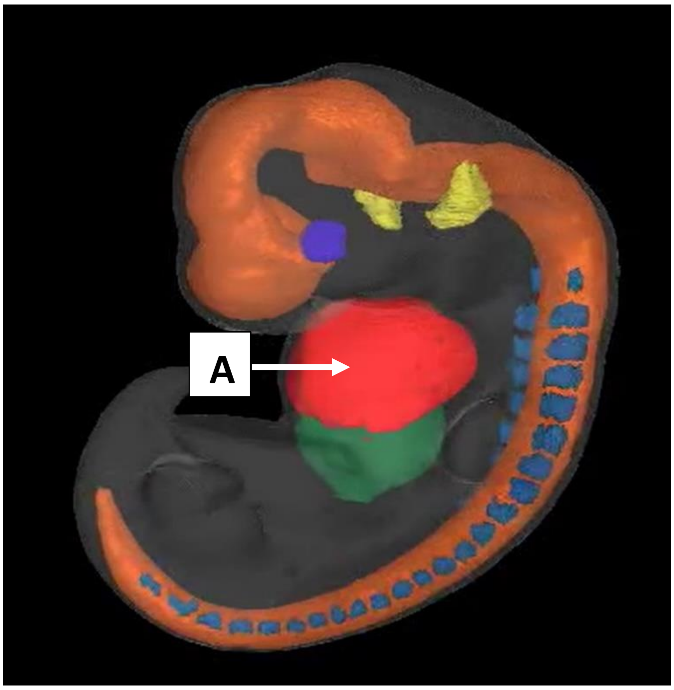
Clicking next to the 3D object will deselect the structure.

For more advanced selection options, right-click on the 3D model and choose: “Show Model Tree”

Example:

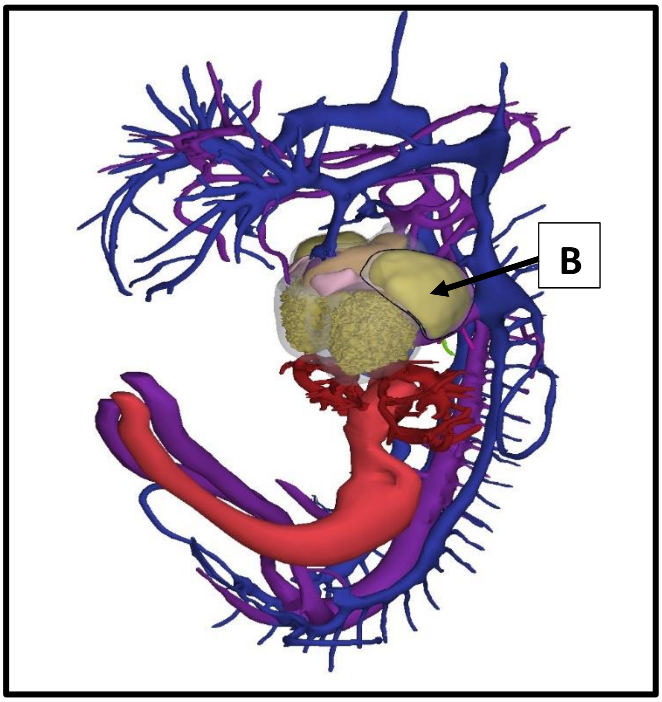


PART 3: SPOTTER ACTIVITY



STATION 1

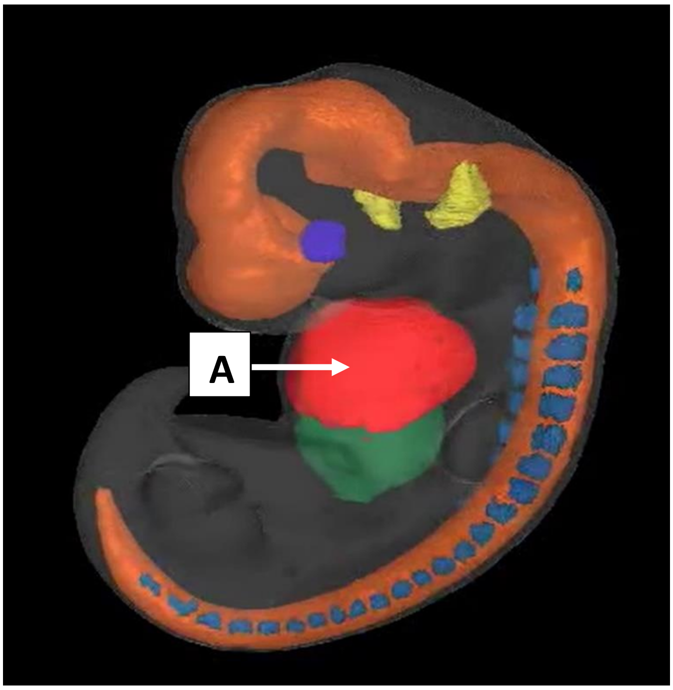
1. At what stage of development is this embryo (in weeks and Carnegie stages)?
2. Identify **Structure A**?
3. **Structure A** is derived?
4. In which week does **Structure A** start to beat?



STATION 2

1. At what stage of development is this embryo (in weeks and Carnegie stages)?
2. Identify **Structure B?**
3. **Structure B** derivatives from which part?

PART 4: SPOTTER Answers



STATION 1

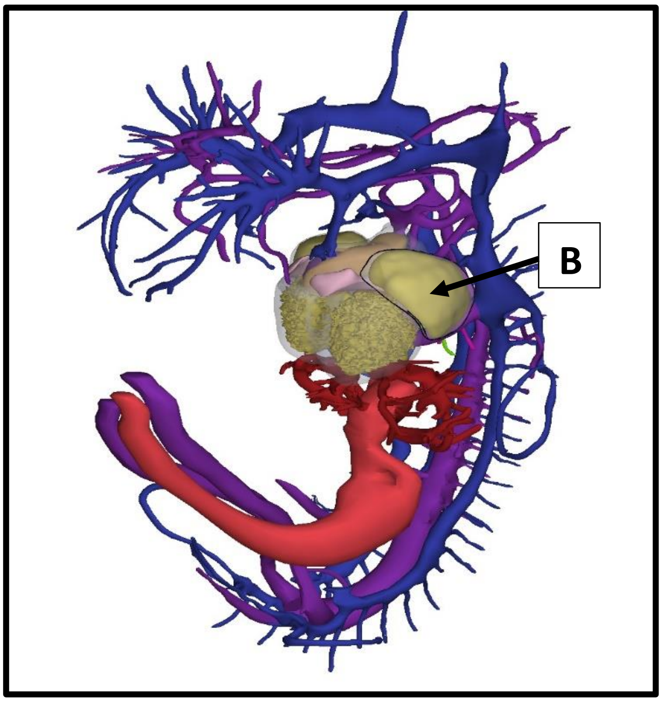
1. At what stage of development is this embryo (in weeks and Carnegie stages)? **CS 14, Week 5**

2. Identify **Structure A**? **The Heart**

3. **Structure A** is derived? **Heart Progenitor Cells**

4. In which week does **Structure A** start to beat?

Week 3



STATION 2

1. At what stage of development is this embryo (in weeks and Carnegie stages)? **CS 16 (Week 6)**

2. Identify **Structure B? Left Atrium**

3. **Structure B** derivatives from which part?

The Primary Heart Field

Appendix Q (Digital Embryology Resources Usage Questionnaire)

Digital Embryology Resources Usage Questionnaire

Thank you for taking the time to complete this questionnaire, your participation is very much appreciated.

Name:

Student ID number (Participation number):

Please read and respond to each question carefully

I. Demographics

Gender

☐ Male | ☐ Female | ☐ Other | ☐ Prefer not to say

Age

☐ (17-20) | ☐ (21-24) | ☐ (25-30) | ☐ (30-35) | ☐ (35+)

Highest previous qualification

☐ (Further Education – e.g. A-levels) | ☐ (Bachelor Degree) | ☐ (Master Degree) | ☐ (PhD)

Do you have any previous experience of learning embryology other than during your current degree? If yes please provide more details.

☐ No | ☐ Yes

Do you have any previous work experience relating to Embryology? If yes please provide more details.

☐ No | ☐ Yes

II. Digital Embryology Resources (HDBR digital heart models & interactive pdfs)

Did you use the DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models & interactive pdfs) to complete Case 2 "Embryology of the heart" MLE tutorial

☐ Yes ☐ NO

If you answered 'yes' please continue to the questions below

If you answered 'no', please state the reasons why you did not access the DIGITAL EMBRYOLOGY RESOURCES (HDBR ATLAS & 3D digital models)

From question 1 to question 15 Please tick the most appropriate answer for each question, where 1 is Strongly Disagree and 7 is Strongly Agree.

1- The DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models & interactive pdfs) improved my understanding of the Embryology of the Heart.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

2- The ability to actively interact with and manipulate the DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models & interactive pdfs) images was important for improving my interpretation of the 3D embryology features in cross-sectional images.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

3- Please describe why your interactions with the HDBR digital heart models were/were not important in improving your understanding of 3D and cross-sectional anatomical features of the heart.

4- Please describe why your interactions with the interactive pdfs of the heart were/were not important in improving your understanding of 3D and cross-sectional anatomical features of the heart.

5- Please describe any OTHER resources you used with the DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models & interactive pdfs) in order to complete any part of the activities in Case 2 Cardiovascular Embryology MLE tutorial.

6- The DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models & interactive pdfs) are a valuable self-directed learning resource for studying the 3D aspects of the embryology of the heart and I wish to use the DIGITAL EMBRYOLOGY RESOURCES for studying embryology again in the future.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

7- Case 2 Cardiovascular Embryology MLE tutorial was a valuable self-directed learning resource for studying the 3D aspects of the embryology of the heart.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

8- I would recommend the DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models & interactive pdfs) and the case activities to other medical students for their embryology learning.

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐5 ☐6 ☐ 7

Strongly Disagree Neutral Strongly Agree

9- Please describe any other suggestions you may have for improving how can we use the DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models & interactive pdfs) in the future.

If you would like to participate in a FOCUS GROUP discussion through ZOOM software about the DIGITAL EMBRYOLOGY RESOURCES (HDBR digital heart models, interactive pdfs) , please provide your email address below. A Newcastle University Certificate of Appreciation signed by Dr Keenan will be awarded to all focus group participants and Free-gift card will be given for the participant at the end of the meeting. Email:

____

Many thanks for your participation.

We are very grateful for the time and effort you have contributed to participating in our study.

Participant consent and use of data

We have developed this questionnaire in order to obtain Newcastle University student perceptions regarding the most challenging topics in anatomy learning and regarding the use of the DIGITAL EMBRYOLOGY RESOURCES (HDBR ATLAS) and 3DP models in anatomy learning.

The data collected from this questionnaire will be used only for purposes of a doctoral thesis, research and publications. Your responses to the questionnaire items and results of your participation will be kept anonymous and confidential. We will use your student ID number as the participant number for identification and NOT your name throughout the research so researchers will not be able to identify you by name.

By submitting this questionnaire, you are consenting for your data to be used for research purposes. Do not submit the questionnaire if you do not consent for us to use your data for research purposes. For more information please contact us by the email provided below.

Dr. Iain Keenan iain.keenan@newcastle.ac.uk

Abdullah Ben awadh a.ben-awadh2@newcastle.ac.uk

Appendix R (Focus Group Questions (Post-COVID 2019)

Focus Group Questions (Post-COVID 19):

Can you tell me if you have any previous anatomy experiences?

Tell me about the challenges in learning you've had in your medical degree so far'?

Tell me about your experiences of learning anatomy so far?

Tell me about your experiences of learning anatomy in terms of the resources you have used?

Tell me about your experiences of learning anatomy using clinical imaging?

Tell me about your experiences of learning with 3DPmodels?

Tell me about your experiences of using the Sectra Educational Portal?

Tell me about your experiences of learning with using the Digital Embryology Resources?

Tell me how you adapted during the pandemic with studying anatomy and the resources you used