Flipped anatomy classroom integrating multimodal digital resources shows positive influence upon students' experience and learning performance

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Abstract
Anatomy is shifting toward a greater focus on adopting digital delivery. To advance digital and authentic learning in anatomy, a flipped classroom model integrating multimodal digital resources and a multimedia group assignment was designed and implemented for first-year neuroanatomy and third-year regional anatomy curricula. A five-point Likert scale learning and teaching survey was conducted for a total of 145 undergraduate health science students to evaluate students' perception of the flipped classroom model and digital resources. This study revealed that over two-thirds of participants strongly agreed or agreed that the flipped classroom model helped their independent learning and understanding of difficult anatomy concepts. The response showed students consistently enjoyed their experience of using multimodal digital anatomy resources. Both first-year (75%) and third-year (88%) students strongly agreed or agreed that digital tools are very valuable and interactive for studying anatomy. Most students strongly agreed or agreed that digital anatomy tools increased their learning experience (~80%) and confidence (>70%). The third-year students rated the value of digital anatomy tools significantly higher than the first-year students (p = 0.0038). A taxonomy-based assessment strategy revealed that the third-year students, but not the first-year, demonstrated improved performance in assessments relating to clinical application (p = 0.045). In summary, a flipped anatomy classroom integrating multimodal digital approaches exerted positive impact upon learning experience of both junior and senior students, the latter of whom demonstrated improved learning performance. This study extends the pedagogy innovation of flipped classroom teaching, which will advance future anatomy curriculum development, pertinent to post-pandemic education.

Keywords
augmented reality, digital anatomy, flipped classroom, gross anatomy education, neuroanatomy, regional anatomy, taxonomy, undergraduate education, videos, virtual reality
INTRODUCTION

Anatomy is the pre-requisite for studying medical and health science courses. For the past fifteen years, anatomical education has shifted toward a greater focus on adopting digital technologies and blended learning strategies (Drake et al., 2009; Uhl et al., 2021). This transformation has been driven by several factors including the increase in student numbers, financial and ethical constraints on cadaver laboratory, and importantly the rapid development of medical technology, which has been further accelerated by the recent Covid-19 pandemic (Dulohery et al., 2021). Modern anatomy teaching is now embracing new modalities for innovation. Digital anatomy, or what is often defined as computer-based three-dimensional (3D) modeling of the human body (Uhl et al., 2021), is advancing given progress and sophistication in computer modeling, virtual and augmented reality (Wickramasinghe et al., 2022).

The development of digital anatomy has been inevitably accelerated by the coronavirus disease 2019 (Covid-19) pandemic, which has induced multifaceted changes in anatomy teaching, resources and staffing, leading to the development and employment of alternative online teaching resources. Since the start of the Covid-19 pandemic in early 2020, there has been a massive switch from face-to-face classes to an online virtual environment across anatomy programs around the world such as in Australia (Pather et al., 2020), New Zealand (Pather et al., 2020), China (Cheng et al., 2021), India (Roy et al., 2020), Singapore (Srinivasan, 2020), South Korea (Yoo et al., 2021), Canada (McWatt, 2021) and United States (Harmon et al., 2021; Attardi et al., 2022; Shin et al., 2022). Lectures were delivered via online classes, video conferences or webinars. Cadaver-based laboratory classes were largely paused or replaced by online teaching using digital tools (Pather et al., 2020; Baptiste, 2021). Coupled with this off-line to online switch, there has been a considerable upskilling of anatomists in the application of digital technologies (Dulohery et al., 2021). A possible long-term change in anatomy education beyond the Covid-19 pandemic is a greater shift from large size “pre-class” lectures toward small-size interactive anatomy laboratory classes adopting a bigger proportion of digital learning (Harmon et al., 2021; Attardi et al., 2022). Anatomy teaching through digital technologies is not new. However, the Covid-19 pandemic induced a “shift” toward digital learning which could ultimately accelerate the implementation of digital teaching in anatomy at a wider scale. As the campus is re-opening, here is the opportunity to adopt innovative and evidence-based teaching strategies together with the available digital resources.

There are a range of digital technologies including the augmented reality (AR), virtual reality (VR), 3D printing, web-based programs and tablet-based apps with supplementary features (Uhl et al., 2021; Wickramasinghe et al., 2022). Approximately three-quarters of anatomy pedagogy research conducted between 2007 and 2017 support the view that digital technologies enhance anatomical education across multiple disciplines including medicine, nursing, dentistry and allied health (Pringle & Rea, 2018). The application of digital anatomy also extends beyond undergraduate education toward postgraduate pre-vocational and vocational clinical trainings. AR and VR anatomy approaches with improved fidelity have been successfully incorporated for not only medical education (Brewer et al., 2012; Bork et al., 2019; Darras et al., 2020) but surgical trainings for advanced practices such as endoscopy (Breimer et al., 2017; Khan et al., 2018; Alwani et al., 2020), laparoscopy (Aoki et al., 2020) and robotics (Bhandari et al., 2020). Virtual dissection resources including the virtual dissection table (Brucoli et al., 2020), multimedia dissector and the virtual human dissector (Houser & Kondrashov, 2018) have been effectively implemented for medical education, providing alternative experience to understand human body complexity and layers of internal structures. Junior medical students perceive the use of virtual dissection as a valuable tool for learning anatomy and radiology (Darras et al., 2020). Indeed, anatomical education using two-dimensional (2D) images and plastic models no longer satisfy learners’ need for establishing their spatial awareness of the structures (Ye et al., 2020). Due to ethical and/or occupational safety restrictions, access to cadavers or cadaveric prospections for anatomy teaching including regional and neuroanatomy curricula is increasingly limited (Stinec et al., 2010; Estai & Bunt, 2016), in particular since the start of the Covid-19 pandemic (Baptiste, 2021). Therefore, multimodal digital approaches could be an effective alternative in teaching anatomy curricula such as regional anatomy (Houser & Kondrashov, 2018; Brucoli et al., 2020) and neuroanatomy, the latter of which poses further challenges to students due to the higher degree of spatial complexity of numerous discrete structures (Rezende et al., 2020). In this context, adopting AR and VR technologies together with virtual dissection resources for teaching regional and neuroanatomy presents a unique advantage in curriculum advancement. Evaluation of anatomical education adopting AR or VR indicates positive outcomes including student engagement (Moro et al., 2017; Triepels et al., 2020; Moro et al., 2021) and problem solving skills (Logeswaran et al., 2021; Stromberga et al., 2021). Virtual reality and AR have been found as valuable anatomy tools that promote learner immersion and engagement within both science and medical students (Moro et al., 2017). Medical students found more motivated and interested in learning anatomical structures using 3D visualization methods compared to 2D resources (Triepels et al., 2020). That said, the impact of digital modalities on anatomy teaching and learning effectiveness is still highly controversial (Triepels et al., 2020; Moro et al., 2021). While students reported that virtual dissection improved their understanding of the clinical applications of anatomy (Darras et al., 2020), a meta-analysis of randomized controlled studies by Zhao et al. (2020) revealed there is a divergency about the learning effectiveness using 3D visualization in anatomy teaching. Moreover, a meta-analysis by Moro et al. (2021) revealed no statistical difference in student anatomy test performance between AR/VR and control groups. This is accompanied by an ongoing shortfall in learner-centred implementation of digital technologies in healthcare education (Logeswaran et al., 2021). There is a need to structurally align digital learning practices with the authentic
learning pedagogy framework such as teamwork and problem solving (Pawlika & Drake, 2016). Therefore, the key question here is how these digital modalities can be effectively adopted to best suit anatomy course design and learning outcomes and advance authentic learning.

The undergraduate anatomy teaching in the Bachelor of Health Science course at Swinburne University of Technology comprises 48 h of first year foundation anatomy, taught to large groups of students primarily as lectures. The anatomy content at the foundation level is entirely system-focused. Preference across the foundation anatomy program is for didactic teaching of large groups of students (500–600 students). The students are provided with electronic copies of the power-point presentations delivered on weekly live online classes, followed by three sessions of anatomy tutorial classes (total six hours) to review eleven body systems. From year 1 (semester 2) onwards, the anatomy teaching varies by majors. Students who choose to major in neuroscience have a further 48 h of neuroanatomy teaching while students who choose to major in biomedical science complete a further 48 h of learning on regional (visceral) anatomy. Both the neuroanatomy and regional anatomy courses comprise 24 h of lectures and 12 h of practical/tutorial classes. The content delivery of both anatomy courses was largely lecture focused. All anatomy tutorial and practical classes are delivered in the Digital Anatomy Laboratory at Swinburne University of Technology, where students use AR, VR, virtual dissection tables, anatomical atlases and anatomical models to explore surface and gross anatomy. No cadaveric materials or cadaveric dissection classes are provided. Two-dimensional or 3D reconstructed cadaveric images were accessible to students via virtual image libraries. Lecturers in anatomy are either medically trained or have a doctoral (Ph.D.) degree in anatomy. Assessment is through quizzes, assignments, and a final written examination.

To build a strong foundation of anatomy, it is of utmost importance to explore creative, appealing and engaging multimodal means that promote proactive learning and long-term, effective retention of knowledge. While digital approaches are being adopted in anatomical education, it is important to promote active learning strategy, not only calibrating content delivery versus the digital resources but also providing students and instructors with clear course alignment and learning objectives. A blended learning strategy that promotes active learning is the flipped classroom mode, which is broadly defined as a teaching approach that reverses the traditional didactic teaching mode focusing on lecture style presentation to interactive activities (e.g., discussion and exercises) in the classroom (Lage et al., 2000; Day, 2018). The flipped classroom where students watch a pre-recorded lecture and undertake assigned reading activities followed by an interactive discussion and problem-solving session are gaining popularity (Day, 2018). Providing students with remotely accessible resources gives them the flexibility to study at their own pace and help manage cognitive load (Abeyesekera & Dawson, 2015).

Recently the flipped mode of anatomical education has been implemented in multiple health disciplines including medicine (Yang et al., 2020; El Sadik & A Abdulmonem, 2021), dentistry (Chutinan et al., 2018; Fleagle et al., 2018) and nursing (Joseph et al., 2021). For the dental anatomy, the flipped classroom educational model has been found to foster active learning, critical thinking, and engagement among students (Kellesarian, 2018). The flipped classroom modality has been found to develop students’ cognitive and psychomotor skills with the support from the instructor and their peers (Kellesarian, 2018). However, in the nursing students, blending new teaching technologies with the flipped classroom activities was found to improve learning outcomes but not necessarily student satisfaction (Missildine et al., 2013). When teaching clinical anatomy to medical students, the flipped classroom model was found to advance students to acquire basic knowledge in an active learning environment (McLaughlin et al., 2014) and improve their performance by activating learning interest and cultivating their thinking ability (Yang et al., 2020). Add to this, the flipped teaching modality was also found to increase the efficiency of instruction in students with a diverse biology background or prior training in anatomy (Houser & Kondrashov, 2018) and compensate for the reduction of anatomy educational hours (El Sadik & A Abdulmonem, 2021). That said, the impact of flipped classroom setting on learning outcomes appeared to vary among student populations depending on their prior study achievement, with a greater beneficial effect on knowledge acquisition and transfer being observed in the lower performing students compared to the higher performing counterparts (Day, 2018). Therefore, the precise influence that the flipped classroom model exerts upon anatomy knowledge acquisition and learning outcome was still largely unclear and highly controversial.

Furthermore, despite the popularity of the flipped classroom mode in higher education, there is little evidence of the utility of combining this hybrid learning approach with multimodal digital approaches for anatomy education. Indeed, it is unknown whether this “dual” pedagogy can be constructively aligned and exerts positive impact upon anatomical education such as student experience and learning performance. It also remains unknown if a digital-based teaching model can be designed and implemented to embrace key components of authentic learning such as teamwork and transportable knowledge (Pawlika & Drake, 2016). To address these questions, based on the principles of Kolb’s Experiential Learning Cycle (Kolb, 1984), a flipped digital anatomy classroom integrating AR and VR technologies plus a multimedia anatomy group assignment was designed and implemented in two undergraduate anatomy curricula, regional (visceral) anatomy and neuroanatomy. This flipped digital anatomy classroom switches teaching focus from large-scale didactic lectures to small-size team based interactive classes with the ultimate goal to advance digital and authentic learning.

Students’ perception regarding their anatomy learning via the flipped classroom model and digital resources were evaluated. Thus, the primary objective of this study was to investigate whether a flipped classroom setting can be delivered successfully in teaching anatomy curricula through integrating multimodal digital approaches. A secondary objective was to determine whether
this “dual” pedagogy approach exerts positive impact upon student experience and anatomical learning outcome.

**MATERIALS AND METHODS**

**Participants and study design**

Participants included two cohorts of undergraduate students enrolled in the Bachelor of Health Sciences at Swinburne University of Technology, Australia, in the academic year of 2021 (n = 145 in total, Table 1). Students from two units (the first-year semester 2 neuroanatomy unit, n = 100; and the third-year semester 1 regional (visceral) anatomy unit, n = 45; Table 1) participated in anatomy education via the flipped classroom model. Participants had previously completed a first-year semester 1 foundation anatomy and physiology unit that was taught to large groups of students (500–600) as lectures and provides a general overview of systems-focused anatomy (Table 1). No flipped classroom teaching model was provided in the first-year foundation anatomy and physiology unit. This study has been approved by the Swinburne University of Technology Human Research Ethics Committee (Ethic ID 20215673–6867). Both anatomy units were 12 weeks long and taught by the same teaching staff. The neuroanatomy unit focused on the structure and function of the central nervous system (Table 2). The gross anatomy materials were delivered via 24 h of lectures, 12 h of laboratory sessions (~15 students per class), 12 h of tutorials. The regional anatomy unit focused on the structure and function of viscera and visceral systems within the thorax, abdomen, and pelvis (Table 2). The gross anatomy materials were delivered via 24 h of lectures and 24 h of laboratory sessions (~15 students per class). Participants included in both cohorts consisted of undergraduate students who had similar prerequisite units that included, but were not limited to, one-semester of Anatomy and Physiology. The gross anatomy content covered in both units was integrated with other disciplines such as physiology and pathology. At the end of the semester and prior to the end of semester examination, students from the two units were invited to participate in an online survey (Microsoft Forms, Microsoft Corp., Redmond, WA). Participation and completion of the survey was anonymous and voluntary. Informed consent was obtained from all participants.

**Flipped digital anatomy classroom**

The format of this flipped classroom teaching was designed based on the principles of David Kolb’s Experiential Learning Cycle (Kolb, 1984), which is one of the most widely used active learning strategy and influential model with emphasis on learning and teaching style (Kolb, 1984; Hydrie et al., 2021). In the flipped classroom model (Figure 1), students were required to learn key anatomy concepts via pre-recorded videos and pre-reading materials prior to attending practical laboratory classes, and within the active learning environment using multimodal digital anatomy tools to define their anatomical knowledge and apply them to a functional context via group-based discussion and cases studies, followed by reflection activities through completing formative tests and delivering a multimedia anatomy group project presentation (Figure 1). The objective of the class design was to improve students’ understanding of human anatomical structures and their function in the context of applied and clinical applications, their ability to construct thoughtful arguments for the integrative nature of human gross anatomy and function, through reflective synthesis of topography and to summarize current research understandings of human body structure and function as they relate to both physiological and pathological conditions.

During the pre-class, students acquired basic anatomy knowledge and concepts through online resources such as instructor’s pre-recorded videos and pre-reading materials supplemented with virtual 2D anatomy images and 3D anatomy models via Canvas (Figure 1). Weekly learning objectives and pre-reading materials were provided to students at the start of each anatomy topic. The anatomy materials of the pre-class activities were constructed as pre-recorded video lectures which were prepared using images from anatomy textbooks such as Clinically Orientated Anatomy (Moore et al., 2017), Atlas of Human Anatomy (Netter, 2018) and Clinical Neuroanatomy (Waxman, 2020), and digital resources such as Anatomage Library, version 7.1 (Anatomage, Inc. Santa Clara, CA), Virtual Human (VH) Dissector, version 5.3.9 (Touch of Life

| Table 1 | Demographic information of study participants |
|---------|-----------------------------------------------|
| **Anatomy curricula** | **Neuroanatomy (n = 100)** | **Regional anatomy (n = 45)** | **p-value** |
| Academic status | First year | Third year | N.A. |
| Prior anatomy exposure | Foundation anatomy and physiology | Foundation anatomy and physiology | N.A. |
| Percentage of survey participation; n (%) | 84 (84.00) | 34 (75.60) | 0.304 |
| Age in years; mean (±SD) | 23.01 (±5.95) | 24.43 (±5.57) | 0.095 |
| Sex | | | |
| Female; n (%) | 65 (65.00) | 30 (66.70) | 0.320 |
| Male; n (%) | 35 (35.00) | 15 (33.30) | |

Note: Participant data describing the student population and demographics in this study. Proportions were statistically analyzed using the Chi square test. Ages are presented as mean (± standard deviation, SD) and statistically analyzed using one-way ANOVA; N.A., not applicable.
TABLE 2  Digital anatomy curricular details

| Anatomy curricula                  | Anatomy themes                                                                 | Digital anatomy resources                                                      |
|-----------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| First-year neuroanatomy           | • Central nervous system organization<br>• Cranium and meninges<br>• Cerebrum<br>• Brain stem<br>• Basal ganglia circuitry<br>• Limbic system<br>• Cranial nerves<br>• Arterial supply to the brain<br>• Functional tracts<br>• Spinal cord<br>• Peripheral nerves and reflex | • Virtual reality<br>• Augmented reality<br>• Online three-dimensional models<br>• Anatomy apps<br>• Virtual human dissection table<br>• Virtual human dissector |
| Third-year regional anatomy       | • Thoracic walls<br>• Lungs and pleura<br>• Diaphragm<br>• Heart and pericardium<br>• Coronary artery and great vessels<br>• Abdominal walls<br>• Inguinal region<br>• Abdominal viscera<br>• Peritoneum<br>• Pelvic floor and perineum<br>• Pelvic viscera<br>• Neurovascular supply to abdominal and pelvic viscera |                                                                                     |

Note: Curricula details describing the anatomy themes of practical laboratory classes covered in the two anatomy units and the digital modalities adopted in the laboratory sessions. Each practical class session is two hours long, during which students undertake group-based learning activities using the provided multimodal digital anatomy resources.

FIGURE 1  Schematic showing the design of the flipped digital anatomy classroom model.

Students REFLECT acquired anatomy knowledge through completing self-directed quizzes and delivering a multimedia anatomy education presentation.

Students APPLY anatomy knowledge to self-guided and group based activities using multimodal digital anatomy resources including AR and VR.

Students LEARN key anatomy concepts from pre-recorded lecture videos and pre-class readings.

Technologies Inc., Aurora, CO) and Sectra Education Library, version 2021 (Sectra AB, Linkping, Sweden). Lecture slides were prepared using PowerPoint program in the Microsoft Office suite (Microsoft Corp., Redmond, WA). Lecture videos were recorded using Echo360 Active Learning Platform (ALP, Echo360, Inc. Reston, VA). Each lecture recording was approximately 30 min in length, with the total recording time per week being approximately 120 min. One week prior to the laboratory session, the corresponding lecture recordings were posted on the online learning management system Canvas, version 6.9.8 (Instructure Inc., Salt Lake City, UT) and made available to students for viewing. Students can either download the pre-recorded lectures from Canvas onto a local computer or view the lecture recordings directly on Canvas at a time and venue that suits their study plan. To enhance students’ understanding using digital resources,
images and videos relating to clinical cases from the Anatomage Library (version 7.1) and Sectra Education Library (version 2021) were captured and included in lecture slides and recordings. The same clinical cases were used in the laboratory practical classes. The virtual 2D anatomy images and 3D anatomy models that were used for pre-class studies were captured or recorded from Anatomage Library (version 7.1). These pre-class activities were designed to provide students with the opportunity to discover and learn the theoretical anatomical knowledge required for activities designed in the digital laboratory class.

For the in-class setting, content covered in the pre-class videos and pre-reading materials were defined in a two-hour laboratory session, in which students had the opportunity to develop their self-guided and self-paced learning through undertaking group-based small class activities (~15 students per laboratory class, 3–5 students per group). The laboratory class was designed to engage students via teacher–student interaction and peer support to enhance student engagement, independent learning, problem solving and clinical reasoning skills, with the content focusing on the contextualization of anatomy education that aimed at understanding the relationship between anatomy and clinical manifestations. Prior to the start of their first practical class on anatomy learning, a two-hour practice training session was provided to all students, allowing them to familiarize with all the digital resource equipment (hardware) and programs (software) provided in the digital anatomy laboratory. Supervised by the instructor, students practiced on how to use and navigate the virtual dissection table, virtual anatomy library, AR and VR programs via touch screen computers and/or VR headsets. During the two-hour practice session, each student was assigned into a study group comprising three to five students who attend the same weekly practical classes and complete the group anatomy project. The practical class on anatomy learning began on the following week. Based on the content covered in the pre-class lectures and learning objectives of the week, the unit convener designed and prepared the practical class manual that included a series of question-based learning activities, pre-selected anatomy images and videos as well as clinical cases integrating the anatomy content covered in the pre-class lectures of the same week together with the AR and VR anatomy resources available in the digital anatomy laboratory. Students were provided with an electronic copy of practical class manuals via Canvas prior to their weekly anatomy practical class. In addition, the pre-selected anatomy images (cadaveric or AR), 3D reconstructed cadaveric model, VR models, videos and medical image (CT or MRI)-based clinical cases were pre-loaded onto either the virtual dissection table or the touch screen computer in the digital anatomy laboratory prior to the start of each class. Each practical class comprised of four working stations, each of which was theme-based and designed to study key structures pertinent to the anatomy content covered in the pre-class lectures. During the two-hour practical class, students rotated through four working stations (approximately 25 min per station) and used pre-loaded digital anatomy images and/or videos supplemented by plastic models to complete learning activities listed on the practical class manual. However, students were not restricted to the images and video resources pre-selected by the unit convener and had the freedom to navigate the anatomy image and video libraries that best suited their own study. Each working station comprised at least two digital modalities for students to complete the designed learning activities. Students had the options to choose virtual dissection table, VH dissector, medical images (CT or MRI), the 3D reconstructed cadaveric images or VR. All AR images, cadaveric images and videos were accessed via large touch screens, allowing interactive learning. Within the digital anatomy laboratory, students together with their team members defined key anatomy concepts, identified and explained the listed structures and their functions through completing theme-based anatomy questions and undertaking group discussions using multiple digital modalities. In so doing, students had the opportunity to improve their knowledge acquisition of 3D anatomy through visualizing, orienting, and navigating the virtual structures. All the anatomy images and videos used in the practical classes were readily available in the AR and VR programs supplied by the manufacturers and accessed by students via computers that were set up in the digital anatomy laboratory. Students were not required to bring their personal electronic devices. Toward the end of the laboratory class, students were required to undertake case studies in a scenario related to the structure(s) covered in both the pre-class lectures and the in-class laboratory session. The group discussion and case study activities (approximately 20 min) were conducted under the guidance of a tutor. Consistent with Swinburne University Graduate Attributes, students engaged in small group discovery experience in laboratory classes using multiple digital anatomy modalities, surface anatomy and medical imaging/diagnostic instrumentation. Prior to the start of the semester, tutors have all been trained with the flipped classroom teaching model and active learning strategy by the unit convener.

The post-class activities included both individual and group-based learning activities. Following each laboratory class, students gauged their knowledge acquired from the pre-class and in-class learning sessions via completing self-directed formative quizzes in the form of multiple-choice questions (MCQs), matching and short answer questions accompanied by immediate feedback through the online learning management system. These self-directed formative quizzes were designed to provide students with feedback that aimed to promote positive learning (Butler & Roediger, 2008). Upon completing each formative quiz, students received immediate feedback about each of the MCQs included in the quiz for self-revision of the relevant anatomy content. Students in each unit were assessed with two online tests (80% of unit total mark) and a multimedia anatomy group project (20% of total unit mark). To gauge students’ learning progress of their knowledge acquired through the flipped class teaching model, students were assessed via mid-semester and end of semester tests, both of which were timed online quizzes comprising image based MCQs and delivered via Canvas. The mid-semester test focused on assessing content delivered during the first half of the semester while the end of semester test focused on content taught for the rest of the semester. Adopting the taxonomy-based assessment strategy (Thompson & O’Loughlin, 2015; Zaidi et al., 2017;
Zaidi et al., 2018; Stringer et al., 2021), MCQs were designed to target knowledge acquisition at three levels (Barley, 2015): “remembering” that focused on memorizing anatomy facts and landmarks, “understanding” that focused on understanding the surface and internal structures relative to surroundings and associated functions, and “applying” that focused on the structural and functional application of the assessed structure(s) in a clinical scenario. The first-year neuroanatomy unit tests comprised 40%, 40%, and 20% of MCQs targeting knowledge acquisition at “remembering”, “understanding” and “applying”, respectively, while the third-year regional anatomy unit tests comprised 20%, 40%, and 40% of MCQs targeting knowledge acquisition at “remembering”, “understanding” and “applying”, respectively. Within the same unit, the mid-semester and end of semester quizzes constituted the same number of MCQs for each of three levels (remembering, understanding and applying).

Moreover, to promote active and authentic learning strategy and provide students with an opportunity to develop multiple academic skills including digital literacy, scientific communication, teamwork, critical thinking and problem solving in the areas of synthesis and application of functional anatomy on a given clinical condition, students were required to complete a multimedia group anatomy assignment. For this assignment, students worked in small groups (3–5 students per group) to collaboratively complete a multimedia anatomy education production incorporating digital technologies. Students were required to provide an overview of the applied anatomy associated with the related structures and the physiological and pathological basis relating to a clinical condition based on the knowledge obtained in the unit, in a manner that a lay audience can understand and briefly discuss long-term functional consequences.

A list of nominated clinical conditions were provided to students in both units at the start of the semester. Students were encouraged to choose their resources of presentation including videos, whiteboard animation, storyboard, or podcast. The duration of group presentation is limited to 15 min (±10%) per group. Students were required to submit their recorded presentations onto Canvas for marking prior to the end of the semester. Presentations were assessed using criteria based on the extent and quality of anatomy knowledge understanding and interpretation, scientific communication, and critical thinking (see Appendix for the marking rubrics). Through this group-based exercise, students had an experiential learning opportunity to undertake their group research and construct thoughtful arguments for the integrative nature of human structure and function and actively apply their knowledge to a given clinical condition for professional communication.

Evaluation and statistical analysis

All questionnaires utilized a five-point Likert scale to evaluate agreement with statements regarding the student perception of digital anatomy modalities and the flipped classroom model (strongly agree = 5, agree = 4, neutral = 3, disagree = 2 and strongly disagree = 1). Questions were written to reflect qualitative observations so that the students could easily provide feedback at the end of the semester. Validity analyses were conducted using SPSS statistical package, version 27 (IBM Corp., Armonk, NY) for items in the survey that addressed student opinions about importance of flipped classroom teaching model using multimodal digital anatomy resources. Questions were split into two constructs: (1) statements regarding student experience of the flipped classroom teaching model, (2) value of the multiple digital anatomy resources presented. Because surveys were conducted for two anatomy units within two cohorts of students, the items related to the two units for two different sets of questions were each assessed separately. Cronbach’s α was used to measure internal consistency and is considered as a measurement of scale reliability. Cronbach’s α coefficients greater than 0.80 indicate high levels of internal consistency, whereas values less than 0.65 suggest that individual items should be deleted to examine whether consistency improves (Altman, 1991).

GraphPad Prism, version 9 (GraphPad Software, Inc., La Jolla, CA) was used for statistical analyses of Likert scale data and test performance. A one-way ANOVA with Dunn’s post hoc testing for comparing data from two or more independent groups (Altman, 1991) was used in order to determine whether there was statistical evidence that the associated student group means are significantly different. Descriptive statistics were used to summarize the responses to each question provided by each student cohort. All data points are reported in means ± standard deviation (±SD). Chi square analysis was used to compare proportions. An alpha level of 5% was used for all statistical significance testing (p<0.05 denotes statistical significance).

RESULTS

Baseline analysis of participants

A total of 145 undergraduate health science students (100 from the first-year neuroanatomy unit and 45 from the third-year regional anatomy unit) participated in the flipped classroom teaching model. Analysis of the survey participation revealed that 84% (84 out of 100) of the first-year students in the neuroanatomy unit and 75.6% (34 out of 45) of the third-year students who studied regional anatomy (viscera and visceral systems) unit completed the online survey at the end of the semester (Table 1). Both cohorts of participants have previously completed a first-year foundation anatomy and physiology unit (Table 1). There was no statistically significant difference in terms of survey participation rate, sex ratio and ages between the two groups of students (Table 1).

Validation of the survey tool

Questions in the scales relating to the student experience of the flipped classroom teaching model and digital anatomy tools were internally consistent, assessed by Cronbach’s alpha (Cronbach a).
Cronbach’s α analysis revealed that questions in the scales relating to the student experience of the flipped classroom (Cronbach’s α = 0.697 for neuroanatomy unit and 0.754 for regional anatomy unit), and the value of multiple digital anatomy resources presented (Cronbach’s α = 0.808 for neuroanatomy unit and 0.812 for regional anatomy unit) were all internally consistent (reliable).

Multimedia anatomy group assignment presentation

Students demonstrated their academic skills in critical thinking, scientific presentation, digital literacies and importantly their capacity in knowledge transfer through completing and presenting a multimedia anatomy group project assignment, which was designed as part of the flipped classroom model to promote authentic learning (Figure 2). Students in both units delivered their group project presentation in a variety of multimedia formats such as screen recorded PowerPoint slide presentations (Figure 2A,C,D) and self-filmed videos using whiteboard drawing (Figure 2B) on a variety of anatomical structures in the context of clinical conditions. The first-year students used their knowledge acquired in the neuroanatomy unit produced a multimedia submission which summarized the symptoms and diagnosis of a neurological or neuropsychiatric condition, the human nervous system structure and function relating to applied and clinical applications, and long-term functional consequences that this neurological or neuropsychiatric condition would exhibit.

The third-year students used the knowledge acquired in the regional anatomy unit and undertook their independent research, summarizing the etiology, causes, pathophysiology, patient presentation, diagnostic findings and clinical reasoning in relation to the anatomy, for a condition selected by the study group. Presentations included interpretation of and common findings on diagnostic imaging modalities. In both units, students were highly innovative in the format of their presentations and the adopted resources. Students either presented the multimedia anatomy project via animated PowerPoint slides (Figure 2A,B,D) or storyboard (Figure 2B). Students undertook their independent research about the selected anatomy structures and clinical conditions and were highly innovative in the format and technology of anatomy content delivery. Some students completed their assignments through using published scientific resources (Figure 2A,C), while others synthesized their anatomy knowledge and illustrated the structure of interest using hand drawn diagrams (Figure 2B) or digital anatomy resources (e.g., cartoon videos) prepared by students themselves (Figure 2D). Through this group-based exercise, students had an experiential learning opportunity to construct thoughtful arguments for the integrative nature of human

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**FIGURE 2** Screenshots of representative multimedia anatomy group assignment presentations. (A) Screenshots of first-year students’ sample presentations on the anatomy of cerebrum cortex and functional cortical regions in the context of dementia via a screen recorded PowerPoint presentation; (B) the anatomy of the basal ganglia circuitry in the context of Parkinson’s disease through a filmed whiteboard video presentation; (C) Screenshots of third-year students’ sample presentations on the anatomy of lower respiratory track in the context of pneumonia via a screen recorded PowerPoint presentation; (D) the anatomy of the pancreas in the context of pancreatic adenocarcinoma through a screen recorded PowerPoint presentation using a student-developed digital anatomy cartoon illustrating pancreatic arterial supply.
structure and function and actively apply their knowledge to a given clinical condition for scientific presentation, allowing them to not only demonstrate their capacity in anatomy knowledge transfer but also develop a range of academic skills for effective and engaging scientific communication. The initiative of embedding a research-based assignment as an assessable item in the anatomy curriculum represents a pedagogy innovation of authentic learning in anatomy.

Evaluation of the flipped classroom

Evaluation of this survey indicated that most students believed that the flipped classroom model helped their independent learning of neuroanatomy and regional anatomy (Table 3 and Figure S1). To determine students’ perception of the flipped classroom on active learning, a teaching and learning survey was performed. The response to the flipped classroom model was consistently positive across both cohorts with approximately 70% of students (Figure S1, first-year neuroanatomy unit = brown boxed columns, third-year regional anatomy unit = black boxed columns) indicating they agreed or strongly agreed that the flipped classroom model “helped their own independent learning” (3.89 ± 0.91 for neuroanatomy, and 3.79 ± 0.95 for regional anatomy, Table 3). There were over 70% of students (Figure S1) indicating that the flipped classroom helped them “understand difficult anatomy concepts” (3.89 ± 0.95 for neuroanatomy, and 3.94 ± 1.08 for regional anatomy, Table 3). These two positive responses were consistent across both student cohorts with no statistical difference between groups (One-Way ANOVA, p = 0.823, Table 3). To determine if there was a difference in the proportion of students’ rating toward the survey statements of flipped classroom teaching between neuroanatomy and regional anatomy student groups, the Chi-squared test was performed (Figure S1). Further analysis revealed no significant difference in the overall proportion of students’ rating between two cohorts of students (Chi-square test, Figure S1). Together, this survey indicated that the majority of students believed that the flipped classroom model helped their independent learning of neuroanatomy and regional anatomy, the former of which was often considered as a difficult subject to teach (Rezende et al., 2020).

Evaluation of the digital anatomy resources

Evaluation of the digital anatomy resources showed that the provided digital tools were highly appreciated and valued by most students in both cohorts, in particular the senior students (Table 3 and Figure S1). To ascertain students’ perception of the digital resources provided in the flipped anatomy classroom, students’ response to these tools and their perceptions of future anatomy learning was evaluated. The response showed that students consistently enjoyed their experience of using an array of AR and VR anatomy resources including the virtual dissection table, VH dissector, 3D-virtual models and anatomy apps. Most students who studied neuroanatomy (75%, Figure S1, brown boxed column) or regional anatomy (88%, Figure S1, black boxed column) strongly agreed or agreed that “digital anatomy tools were very valuable, interactive and stimulating”. There were over 70% of students (Figure S1) in both cohorts who strongly agreed or agreed that digital anatomy tools make them “feel more confident in studying courses that require anatomy knowledge in the future” (3.95 ± 0.75 for neuroanatomy unit, and 4.08 ± 0.75 for regional anatomy unit, p = 0.412, Table 3). Students’ learning experience using the digital anatomy tools were consistently positive for both cohorts (Figure S1), demonstrated by both cohorts consistently viewing that “Flipped classroom model helped their own independent learning” (3.89 ± 0.91 for neuroanatomy unit, and 3.79 ± 0.95 for regional anatomy unit, p = 0.605, Table 3), and that “Flipped classroom model helped me understand difficult anatomy concepts” (3.89 ± 0.95 for neuroanatomy unit, and 3.94 ± 1.08 for regional anatomy unit, p = 0.823, Table 3). 77% of students who studied neuroanatomy and 85% of students who studied regional anatomy (3.96 ± 0.75 for neuroanatomy unit and 4.11 ± 0.84 for regional anatomy unit, p = 0.361, Table 3) strongly agreed or agreed that digital anatomy tools enhanced their learning experience and interest in the course. The third-year students who studied regional anatomy consistently rated the digital anatomy tools more highly than the first-year students studying neuroanatomy. While in two questions no statistical significance was detected, the rating of digital anatomy tools regarding their value, interactivity and simulation was significantly higher for the regional anatomy unit compared to the neuroanatomy unit (4.44 ± 0.75 for regional anatomy unit, 3.96 ± 0.87 for neuroanatomy unit, p = 0.0038, Table 3). To determine if there was a difference in the proportion of students’ rating toward the five survey statements of multimodal digital anatomy modalities between neuroanatomy and regional anatomy student groups, the Chi-squared test was also performed and revealed no significant difference in the overall proportion of students’ rating between two cohorts of students (Figure S1), although there was a trending difference in the rating proportion of digital anatomy tools regarding their value, interactivity and simulation between the two group of students (p = 0.088, Figure S1).

Evaluation of student performance

Evaluation of the mid-semester and end of semester quizzes’ marks showed a positive trajectory of students’ performance in anatomy learning, with the senior (third-year) students, but not the junior (first year) students, showing a significant improvement in their assessment relating to clinical application (Table 4). To determine the effectiveness of the flipped anatomy class teaching model integrating multimodal digital resources on students’ learning outcomes such as their learning progress in anatomy knowledge and critical thinking skills, academic performance was assessed via two timed MCQ-based online tests, with one being delivered in the middle of semester and the other at the end of the semester. To understand the levels of cognitive reasoning such as synthesis of anatomy knowledge and clinical application following the flipped classroom model, MCQs were written to assess three levels of knowledge acquisition (remembering,
Students perceptions of the flipped anatomy classroom and digital resources

| Statement                                                                 | Neuroanatomy mean (±SD) | Regional anatomy mean (±SD) | p-value |
|--------------------------------------------------------------------------|-------------------------|----------------------------|---------|
| I found digital anatomy tools very valuable, interactive and stimulating  | 3.96 (±0.87)            | 4.44 (±0.75)               | 0.0038* |
| Digital anatomy tools enhanced my learning experience and interest in the course | 3.96 (±0.75)            | 4.11 (±0.84)               | 0.361   |
| Digital anatomy tools made me feel more confident in studying courses that require anatomy knowledge in the future | 3.95 (±0.75)            | 4.08 (±0.90)               | 0.401   |
| “Flipped classroom” model helped my own independent learning              | 3.89 (±0.91)            | 3.79 (±0.95)               | 0.605   |
| “Flipped classroom” model helped me understand difficult anatomy concepts | 3.89 (±0.95)            | 3.94 (±1.08)               | 0.823   |

Note: Students’ responses relating to the experience of the flipped classroom and the value of multiple digital anatomy resources presented in the two units. Number of respondents: for neuroanatomy unit (n = 84) and for regional anatomy unit (n = 34). Answers were reported on a five-point Likert scale where strongly agree = 5; agree = 4; neutral = 3; disagree = 2; strongly disagree = 1. Values are presented as mean (± standard deviation, ±SD) and statistically analyzed using one-way ANOVA with Dunn’s post hoc.

#Statistical difference at p < 0.05.

Student performance on mid-semester and end of semester quizzes

| Anatomy curriculum | Quiz level of anatomy knowledge | Mid-semester quiz mark; mean % (±SD) | End of semester quiz mark; mean % (±SD) | p-value |
|--------------------|---------------------------------|--------------------------------------|----------------------------------------|---------|
| Neuroanatomy       | Remembering                     | 72.6 (±4.0)                          | 71.1 (±3.4)                            | 0.396   |
|                    | Understanding                   | 64.4 (±15.1)                         | 61.6 (±12.5)                           | 0.605   |
|                    | Applying                        | 50.60 (±32.7)                        | 54.1 (±21.0)                           | 0.329   |
| Regional anatomy   | Remembering                     | 71.3 (±18.9)                         | 71.5 (±13.9)                           | 0.481   |
|                    | Understanding                   | 60.2 (±13.2)                         | 65.1 (±8.7)                            | 0.378   |
|                    | Applying                        | 50.5 (±14.9)                         | 63.1 (±15.7)                           | 0.045*  |

Note: Students’ study progress following the delivery of flipped classroom teaching model integrating digital anatomy resources were assessed via comparing their performance between the timed mid-semester and end of semester online quizzes. Number of participants in the online quizzes for neuroanatomy unit (n = 84) and for regional anatomy unit (n = 34). The data of quiz marks were presented as mean percentage (± standard deviation, ±SD) and statistically analyzed using one-way ANOVA with Dunn’s post hoc.

#Statistical difference at p < 0.05.

DISCUSSION

This study presents a new model of flipped anatomy classroom through integrating multimodal digital strategies in class delivery and assessment. This is the first study that has investigated the influence of flipping the anatomy classroom on learning experience and performance when integrating multimodal digital resources in two undergraduate anatomy curricula. The present study indicates that this flipped anatomy teaching model is a feasible and effective method to facilitate the delivery of anatomy curricula, leading to positive learning experience. Majority of first- and third-year students appreciated the value of anatomy presented in this flipped classroom setting with available to support the designed content. Taken together, these results collectively indicate that the flipped classroom model improved learning effectiveness in the senior students, who possess a higher level of motivation and self-efficacy compared to junior students (Abdel Meguid et al., 2020).
the third-year students showing a significantly higher rating on digital resources and a better performance on the clinical application of anatomy knowledge compared to the first-year students. Embedding a multimedia anatomy project as part of the flipped classroom model not only promotes active learning but provides new evidence that an innovative assessment approach supplement to traditional exams can be incorporated to encourage authentic learning and knowledge translation, shifting the current paradigm of anatomy assessment further away from its didactic history. Together, this study demonstrates that a flipped classroom model focusing on practically applied anatomy can be successfully integrated with multiple digital modalities for immersive learning. Assisting students to establish an active and independent learning technique is a major advantage of this teaching modality and could be useful in any educational setting, which is particularly pertinent to digital learning and simulation.

This study practically implemented “in-class” group-based learning activities and a “post-class” group project assignment to reinforce experiential learning strategy, which has significantly extended the flipped classroom model. Many studies suggest that the production of experiential learning space was mediated through social interactions and engagement (Pipitone & Raghavan, 2017). Students’ learning experiences and learning approaches underpin the quality of their learning outcomes (Ning & Downing, 2010; Mørk et al., 2021). In the present mode of flipped classroom, teaching was shifted toward a greater focus from large-sized didactic lectures toward small-sized practical classes, where students were exposed to the learning concepts prior to the classroom before their “in-class” time. The in-class setting encouraged active learning with an emphasis on knowledge generation, where students applied the basic knowledge acquired from their pre-class learning to undertake problem-based learning activities via team-based discussion and used clinical cases to illustrate points of knowledge in a stimulating and flexible environment. This learning and teaching style allowed students to take control of the development of their cognitive and social skills while the instructor facilitated and supported the learning process, hence fostering student autonomy. In so doing, students actively applied their anatomy knowledge to evaluate, analyze and reflect their skills under an enriched learning environment accompanied by an instructor. Therefore, the group discussion-orientated laboratory class setting promoted not only student-tutor interactions but importantly the student–student interactions, facilitating peer-support and peer-learning. In this study, the flipped classroom integrating digital resources showed promising effects on anatomical education, demonstrated by students’ positive perception toward their independent learning and understanding of difficult concepts, implying an improved autonomous learning ability.

Moreover, embedding a “post-class” multimedia anatomy group assignment represents an innovative approach to practically apply authentic learning pedagogy in anatomy, significantly extending the design of a flipped classroom curriculum. Authentic learning is a topical area in health science education. In anatomy, cadaver-based teaching and the interdisciplinary training opportunities by multidisciplinary health professionals offers boutique opportunities to apply authentic learning in anatomy (Pawlina & Drake, 2016). Teamwork, interprofessional learning, and reflection are the key components (Pawlina & Drake, 2016). When moving into a digital era, in particular when cadaveric-based teaching materials are not accessible, alternative approaches are needed to embrace authentic learning of anatomy. Anatomy is not only essential to medical practice but an important scientific discipline that requires effective professional communication to a wider community. Therefore, in addition to exam-based traditional assessments, it is important to equip students with research and scientific communication skills to practically translate their anatomy knowledge outside of the classroom. O’Loughlin & Griffith (2020) adopted reflective writing in an undergraduate anatomy course which was found to facilitate the improvement of cognitive skills and learning progress. Ansety (2017) implemented an inquiry-based project to engage students in anatomical understanding and practically apply their disciplinary knowledge outside of classroom. In this study, as part of the flipped digital anatomy classroom design, a multimedia anatomy group assignment was embedded as part of the performance measures with the aim to develop students’ research, scientific presentation, critical thinking and digital literacy skills in the areas of functional anatomy application. Completing a collaborative group project was designed to help students develop an active learning strategy involving research, problem solving and teamwork. Through this group-based exercise, students had an opportunity to construct thoughtful arguments for the integrative nature of human structure and function and actively applying their knowledge to a given clinical condition. The multimedia anatomy project was a worthwhile journey and provided students with a ‘work-related’ learning experience outside of a traditional classroom, which is an effective pedagogical tool to integrate theory and practice in future anatomical education. Implementing an assessment involving project development and research presentation in anatomy curricula actively applies the “authentic learning” pedagogy (Pawlina & Drake, 2016) in anatomy, representing an innovative pedagogical strategy to support the transfer from digital-based learning to real-world application of anatomical knowledge (Saltarelli et al., 2014). This multimedia anatomy project approach not only promotes active learning but ultimately advances anatomy discipline and research innovation, providing new evidence that innovative assessment approaches supplement to traditional exams can be incorporated in anatomy curriculum to encourage experiential learning and knowledge translation. Furthermore, it was also a rewarding process for educators who were highly impressed by students’ capability and creativity in generating digital anatomy education resources. This, in turn, not only echoes the ‘students as partners’ teaching practice (Barradell & Bell, 2021), as it not only reinforces student-centered philosophy but improves educators’ own teaching and research design. Taken together, the multimedia anatomy group assignment approach will shift the current
paradigm of anatomy education further away from its didactic history (Ansey, 2017), advancing knowledge transfer.

This study indicates that a flipped classroom model through combining digital resources together with a multimedia group project is an effective approach to advance anatomy knowledge in clinical application and critical thinking in advanced learners, supporting the notion of using alternatives to traditional teaching methods in anatomy (Losco et al., 2017). While the flipped classroom teaching model is becoming increasingly popular in health education, its impact on student satisfaction and learning outcomes was indeed highly controversial (Fleagle et al., 2018; Roy et al., 2020; El Sadik & Al Abdulmonem, 2021). A randomized study by Yang et al. (2020) identified a significantly higher assessment score in medical students from the flipped classroom group compared to their peers in the control group, indicating a positive learning outcome on human anatomy teaching following the flipped classroom model. A similar result was also found in another study conducted in nursing students (Joseph et al., 2021). Fleagle et al. (2018) found adopting the flipped classroom strategy in a dental gross anatomy course led to significantly higher student grades in the final laboratory examination, although not the first two examinations, indicating an effect upon learning progress. In contrast, a study of an undergraduate foundation anatomy and physiology unit revealed no significant difference in student examination outcomes between traditional and flipped classroom model (Jafar & Sitther, 2021). Furthermore, a non-randomized controlled study also found the flipped model significantly improved students’ problem-solving abilities but exerted no significant effect on critical thinking compared to the control group (Hwang & Oh, 2021). Therefore, although participants in the flipped learning group were consistently satisfied with the teaching model than those in the control group, the precise role of flipped classroom in learning effectiveness is yet to be fully understood. Add to this, as aforementioned above, while many studies showed that AR, VR and virtual dissection tables were valuable tools to integrate clinical cases and significantly improve student engagement (Moro et al., 2017; Darras et al., 2020), and motivation (Triepels et al., 2020), and confidence (Yudkowsky et al., 2013; Locketz et al., 2017), particularly in complex cases (Stromberga et al., 2021), the role of digital tools upon student learning outcomes as assessed by examinations were not uniformly consistent (Meyer et al., 2016; Moro et al., 2017; Afsharpour et al., 2018; Zhao et al., 2020). Studies by Moro et al. (2017, 2021) found that AR or VR anatomy did not enhance test performance in science and medical students. Similarly, Meyer et al. (2016) found no association between app use and anatomy score. In contrast, students who used virtual dissection table in a musculoskeletal gross anatomy course performed significantly better in laboratory examination compared to their peers who used cadavers (Afsharpour et al., 2018). Establishing spatial awareness of the human structures is necessary for establishing a contextualized understanding of human body structure and function. Both educators and learners could benefit from adopting digital modalities that provide immersive learning experience and facilitate users to establish spatial understanding as a priority in anatomy. When access to cadavers or cadaveric prosections for anatomy teaching including regional and neuroanatomy curricula is increasingly limited (Stimec et al., 2010; Estai & Bunt, 2016), VR and AR anatomy provides alternative experience to understand structural complexity in learning clinical anatomy (Darras et al., 2020), through which learners develop a deeper understanding of surface anatomy and internal structures relative to the surroundings (Deng et al., 2018). AR including virtual dissection table is a valuable tool for the integration of clinical cases and pathology content into anatomy learning (Darras et al., 2019; Dukan et al., 2021). In this study, multimodal digital resources involving AR and VR have been used for neuroanatomy and regional (visceral) anatomy education, focusing on surface anatomy and internal structures in both physiological and pathological settings. Combining VR and AR for teaching the same structure(s) was found to help students develop a deeper understanding in anatomy (Deng et al., 2018), indicating a unique role of multimodal digital resources in anatomy. Therefore, to gauge the impact of flipped anatomy classroom integrating multimodal digital resource on learning performance such as learning progress, in the present study, a Bloom's taxonomy-based assessment strategy that stratifies assessment activities into different cognitive levels (Thompson & O'Loughlin, 2015; Zaidi et al., 2018; Stringer et al., 2021) was adopted to design MCQ questions at three categories (Barkley, 2015): “remembering” that focused on knowing the anatomy facts, “understanding” that focused on contrasting and comparing anatomy knowledge, and “applying” that focused on pushing clinical reasoning and critical thinking skills. Analysis of the mid- and end of semester quizzes outcomes showed no significant differences in students’ performance relating to the “remembering” and “understanding” questions for both units. No significant differences were found in the first-year students’ marks relating to the “applying” level of questions in the neuroanatomy unit. Interestingly, the third-year students in the regional (visceral) anatomy unit demonstrated a significant improvement in their accuracy in answering the “applying” level of questions, which is a higher level of learning category. Results of this study therefore indicate that, instead of playing a “blanket” role upon learning outcomes, the flipped classroom model integrating multiple digital modalities could play a more effective role in promoting anatomy learning in advanced learners. The different student performance identified from the first- and third-year students’ cohorts is intriguing and is likely due to an effect of students’ academic status and self-efficacy, which has been shown to influence academic performance in anatomy (Abdel Meguid et al., 2020). Students’ self-efficacy in active learning can be influenced by the learning environment (Abdel Meguid et al., 2020), which in turn facilitates the subjective confidence that positively correlates with anatomy learning performance (Locketz et al., 2017). Indeed, a stronger relationship between academic performance and study motivation has been found in the senior anatomy students compared to the junior counterpart (Abdel Meguid et al., 2020). Therefore, the finding of student performance indicates senior or advanced learners are more likely to benefit from the flipped classroom teaching model in their learning outcome, and that student self-efficacy is a key factor that will influence the learning outcome following an active learning pedagogy (e.g., the flipped teaching model).
Consistently students’ perception of appreciating the value of digital anatomy resources in improving learner confidence and learning experience is another clear positive outcome of this study. Most students in both anatomy units viewed digital anatomy tools very interactive and stimulating, enhancing not only their learning experience but importantly their confidence and interest in studying anatomy in the future, the latter of which is expected to promote vertical integration of anatomy learning. The third-year students who studied regional (visceral) anatomy consistently rated the digital anatomy tools more highly than those who studied the first-year neuroanatomy. In particular, the third-year students’ rating on digital resources regarding their value and interactive nature was significantly higher than the first-year students. The factors that underly this rating difference is complex and can be influenced by multiple effects including the students’ academic status (first-year vs. third-year) and the technical capacity of current digital tools on anatomy topics (regional viscera anatomy vs neuroanatomy). Abdel Meguid et al. (2020) identified a strong correlation between study motivation and students’ academic seniority, which could influence their perception of the value of provided learning resources. Moreover, the technical capacity of available digital resources that support the anatomy content (neuroanatomy vs regional anatomy) could also contribute, at least partially, to this rating difference between two units. Within the Swinburne Digital Anatomy Laboratory, there were relatively more sophisticated digital resources with high fidelity available to study regional (visceral) anatomy compared to neuroanatomy. While surface structures of the brain and spinal cord are readily accessible using both augmented and virtual tools, the visualization of key internal structures such as functional fiber tracts within the brain or spinal cord is poorly presented in many digital anatomy models. Therefore, the fine nervous system structures are often relatively harder to discriminate compared to gross internal organ structures by students, which could be independent of their academic status. The technical capacity of current digital resources such as fidelity and sophistication that supports the teaching content (regional visceral anatomy vs neuroanatomy) could influence students’ perception of the digital tools’ value in anatomy. Add to this, the different time exposure to multimodal digital modalities between the two units may also contribute to the rating difference in digital tools. There were 24 h of laboratory sessions in the third-year regional (visceral) anatomy unit compared to 12 h in the first-year neuroanatomy unit. The amount of time spent in the digital anatomy laboratory could influence the extent of students’ experience, engagement, and competence toward the various digital technologies. In this study, within the rich learning environment, students were provided with the freedom to choose their preferred digital resources, enabling learning autonomy. Hence, the third-year students in the regional anatomy unit had more opportunities to explore more sophisticated digital resources than the first-year students in the neuroanatomy unit. Taken together, the present study indicates that the flipped classroom model is compatible with the implementation of multimodal digital resources in practical classes, which experts positive influence upon student engagement, confidence and learning experience in anatomy. Finding of this study also indicates that the technical capacity of digital anatomy resources could influence students’ perception toward the value of using these digital resources in anatomy learning over the long-term.

Collectively, results of this study suggest that the majority of health science students in first and third-year anatomy units at Swinburne University of Technology had positive perceptions of the flipped classroom and digital resources. This study extends the current flipped classroom model via practically integrating digital and authentic learning of anatomy and identifies its roles in advancing cognitive and problem-solving skills in advanced learners who possess a higher level of self-efficacy. This study also highlights the importance of adopting a taxonomy-based assessment design strategy to categorize the measurement of learning outcomes in order to gain a precise understand of curriculum effectiveness when implementing a new teaching model. Together, findings of this study will advance the pedagogy innovation of flipped classroom teaching model on digital and authentic learning of anatomy, which will prompt future new research focusing on evaluating learning outcomes of anatomy curricula integrating the flipped and digital teaching strategies.

Limitation of the study

There are several limitations associated with this study. The sample size of each student cohort in this study was relatively small. Due to the anonymous nature of the survey, the authors were not able to directly compare the extent of flipped classroom experience with students’ learning outcomes. Moreover, there was no control group that was taught using the “non-flipped” teaching method in parallel. Due to major changes in the curriculum including anatomy content and teaching staff since 2020 (inclusive), a historical group was also not available. As a result, the study could not directly evaluate the curriculum effectiveness of the flipped anatomy classroom model through evaluating student performance between the flipped and control teaching methods. There are also limitations associated with the survey questionnaire such as limited items being included in the Digital Anatomy Teaching and Learning Survey and the use of double- and triple-barrelled questions. Therefore, a randomized controlled trial that involves a larger sample size and revised survey questionnaire should be conducted to precisely determine the curriculum effectiveness of the flipped classroom setting integrating digital resources on student performance in the future.

In addition, students were given unlimited and flexible access to the pre-class activities, it was impossible to measure their time spent on each of those activities. Likewise, during the “in-class” laboratory session, students had the option to choose the digital resources that best suit their study pace, which was indeed part of the curriculum design that aimed to promote active and independent learning. Due to the heterogenous nature, it was impossible to measure the extent of usage of which resources the students chose to use such as the duration of time and each student’s preferences toward individual digital modalities. Hence, it was impossible to correlate the
quiz results with the efficiency of the pre-class activities or in-class activities, which warrants future investigation. Another limitation of the study is the lack of formal evaluation of student perception of the multimedia student group presentation, which was not incorporated in the survey. A separate study will be required to understand the impact of research-based student assignment on active learning, however which is beyond the remit of this study.

Finally, only short-term student learning experience and outcomes were assessed in this study. It is possible that the flipped classroom approach integrating multimodal digital resources could help enhance students’ long-term learning outcome and cognitive skills. Therefore, longitudinal studies are also required to identify the long-term impact that the flipped classroom model plays in anatomical education across multiple disciplines.

**Future perspectives**

Results of this study will advance the development of evidence-informed approaches to promote anatomical education and authentic learning in the future, pertinent to effective anatomical teaching in the pandemic era of COVID-19 (Mishall et al., 2022; Shin et al., 2022). Future studies that explore this educational model in medical, dental and allied health anatomy regarding students’ engagement and performance as well as academic perceptions are needed. This study extends pedagogy innovation of the flipped classroom teaching model in anatomy through combining advanced digital modalities together with a multimedia student group presentation, advance digital and authentic learning. While digital approaches are being adopted in anatomy, digital anatomy education is not a simple technical conversion. Different digital anatomy tools possess supplementary features; hence selection needs to best meet graduates’ attributes and a constructive alignment between learning tasks and performance measures for curriculum design.

Following the success of the flipped digital anatomy classroom described here and the positive feedback from students, the teaching modality is being implemented within the School of Health Sciences at Swinburne University of Technology for other anatomy curricula. In addition, the recent university-wide course review at Swinburne University of Technology has included a review of teaching in the anatomy curricula across all health sciences and allied health disciplines, and there is a willingness to introduce a greater proportion of digital learning strategies and more experiential learning activities. In the future, strategic planning for the digital delivery of anatomy curriculum coupled with formal evaluation of learning effectiveness is required.

**CONCLUSIONS**

The flipped classroom model presented in this study switches anatomy teaching focus from large-scale didactic lectures to small-size team based interactive classes and provides significant contribution to pedagogy innovation through integrating multimodal digital resources and a multimedia student group assignment, advancing digital and authentic learning. The authors conclude that the “dual” pedagogy is a feasible and effective approach for anatomy teaching, which will shift the current paradigm of anatomy teaching further away from its didactic history. Results presented in this study indicate the flipped classroom model exerts positive influence upon students’ perception of anatomy learning experience and confidence. The flipped teaching model facilitates active learning that supports study performance of learners. Findings of this study also highlight the necessity of not only adopting a taxonomy-based assessment strategy to precisely evaluate assessment-based learning outcomes but constructing a broader survey which runs through with Principal Components Analysis to confirm student learning experience when implementing a new teaching strategy. As universities resume the on-campus experience, findings of this study provide new evidence that will support the next phase of anatomical science education provision as we enter the post-pandemic phase and beyond.

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**CONFLICT OF INTERESTS**

The authors declare no conflict of interests.

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**REFERENCES**

Abdel Meguid EM, Smith CF, Meyer AJ. 2020. Examining the motivation of health profession students to study human anatomy. Anat Sci Educ 13:343–352.

Abeysekera L, Dawson P. 2015. Motivation and cognitive load in the flipped classroom: Definition, rationale and a call for research. High Educ Res Dev 34:1–14.

Afsharpoor S, Gonsalves A, Hosek R, Partin E. 2018. Analysis of immediate student outcomes following a change in gross anatomy laboratory teaching methodology. J Chiropr Educ 32:98–106.

Altman DG. 1991 Practical Statistics for Medical Research. 1st Ed. London, UK: Chapman & Hall. 624 p.

Alwani MM, Svenstrup TJ, Bandali EH, Sharma D, Higgins TS, Wu AW, Shipchandler TZ, Illing EA, Ting JY. 2020. Validity testing of a three-dimensionally printed endoscopic sinonasal surgery simulator. Laryngoscope 130:2748–2753.

Ansety LM. 2017. “Applying anatomy to something I care about”: Authentic inquiry learning and student experiences of an inquiry project. Anat Sci Educ 10:538–548.

Aoki T, Koizumi T, Mansour DA, Fujimori A, Kusano T, Matsuda K, Nogaki K, Tashiro Y, Hakozaki T, Wada Y, Shibata H, Tomioka K, Hirai T,
Yamazaki T, Saito K, Enami Y, Koike R, Mitamura K, Yamada K, Watanabe M, Otsuka S, Murakami M. 2020. Virtual reality with three-dimensional image guidance of individual patients’ vessel anatomy in laparoscopic distal pancreatectomy. Langenbecks Arch Surg 405:381–389.

Attardi SM, Harmon DJ, Barremkala M, Bentley DC, Brown KM, Dennis JF, Goldman HM, Harrell KM, Klein BA, Ramninan CJ, Farkas GJ. 2022. An analysis of anatomy education before and during Covid-19: August-December 2020. Anat Sci Educ 15:5–26.

Baptiste YM. 2021. Digital feast and physical famine: The altered ecosystem of anatomy education due to the Covid-19 pandemic. Anat Sci Educ 14:399–407.

Barkley A. 2015. Flipping the college classroom for enhanced student learning. N Am Coll Teach Agr J 59:240–244.

Butler AC, Roediger HL. 2008. Feedback enhances the positive effects and reduces the negative effects of multiple-choice testing. Mem Cognit 36:604–616.

Barradell S, Bell A. 2021. Is health professional education making the most of the idea of ‘students as partners’? Insights from a qualitative research synthesis. Adv Health Sci Educ Theory Pract 26:513–580.

Bhandari M, Zeffiro T, Reddiboina M. 2020. Artificial intelligence and robotic surgery: Current perspective and future directions. Curr Opin Urol 30:48–54.

Bork F, Stratmann L, Enssle S, Eck U, Navab N, Waschke J, Kugelmann D. 2019. The benefits of an augmented reality magic mirror system for integrated radiology teaching in gross anatomy. Anat Sci Educ 12:585–598.

Breimer GE, Haji FA, Bodani V, Cunningham MS, Lopez-Rios AL, Okrainec A, Drake JM. 2017. Simulation-based education for endoscopic third ventriculostomy: A comparison between virtual and physical training models. Oper Neurosurg (Hagerstown) 13:89–95.

Brewer DN, Wilson TD, Eagleson R, de Ribaupeire S. 2012. Evaluation of neuroanatomical training using a 3D visual reality model. Stud Health Technol Inform 173:85–91.

Brucoli M, Boffano P, Pezzana A, Sedran L, Boccafoschi F, Benech A. 2020. The potentialities of the Anatomage table for head and neck pathology: Medical education and informed consent. Oral Maxillofac Surg 24:229–234.

Cheng X, Chan LK, Pan SQ, Cai H, Li YQ, Yang X. 2021. Gross anatomy education in China during the Covid-19 pandemic: A national survey. Anat Sci Educ 14:8–18.

Chutinan S, Riedly CA, Park SE. 2018. Student performance in a flipped classroom dental anatomy course. Eur J Dent Educ 22:e343–e349.

Darras KE, Spouge R, Hatala R, Nicolaou S, Hu J, Worthington A, Krebs C, Forster BB. 2019. Integrated virtual and cadaveric dissection laboratories enhance first year medical students’ anatomy experience: A pilot study. BMC Med Educ 19:366.

Darras KE, Forster BB, Spouge R, de Bruin AB, Arnold A, Nicolaou S, Hu J, Hatala R, van Merriënboer J. 2020. Virtual Dissection with clinical radiology cases provides educational value to first year medical students. Radiology:56:200534.

Day LJ. 2018. A gross anatomy flipped classroom effects performance, retention, and higher-level thinking in lower performing students. Anat Sci Educ 11:565–574.

Deng X, Zhou G, Xiao B, Zhao Z, He Y, Chen C. 2018. Effectiveness evaluation of digital virtual simulation application in teaching of gross anatomy. Ann Anat 218:276–282.

Drake RL, McBride JM, Lachman N, Pawlina W. 2009. Medical education in the anatomical sciences: The winds of change continue to blow. Anat Sci Educ 2:253–259.

Dukan R, Uhl JF, Delmas V, Chahim M, Masmejean EH. 2021. Three-dimensional reconstruction of the upper limb from anatomical slices of the Korean visible human: Simulation and educational application. Surg Radiol Anat 43:547–558.

Dulohery K, Scully D, Longhurst GJ, Stone DM, Campbell T. 2021. Emerging from emergency pandemic pedagogy: A survey of anatomical educators in the United Kingdom and Ireland. Clin Anat 34:948–960.

El Sadik A, Al Abdulmonem W. 2021. Improvement in student performance and perceptions through a flipped anatomy classroom: Shifting from passive traditional to active blended learning. Anat Sci Educ 14:482–490.

Estai M, Bunt S. 2016. Best teaching practices in anatomy education: A critical review. Ann Anat 208:151–157.

Fleagle TR, Borchering NC, Harris J, Hoffmann DS. 2018. Application of flipped classroom pedagogy to the human gross anatomy laboratory: Student preferences and learning outcomes. Anat Sci Educ 11:385–396.

Harmon DJ, Attardi SM, Barremkala M, Bentley DC, Brown KM, Dennis JF, Goldman HM, Harrell KM, Klein BA, Ramninan CJ, Richtsmeier JT, Farkas GJ. 2021. An analysis of anatomy education before and during Covid-19: May-August 2020. Anat Sci Educ 14:132–147.

Houser JJ, Kondrashov P. 2018. Gross anatomy education today: The integration of traditional and innovative methodologies. Mo Med 115:61–65.

Hwang Y, Oh J. 2021. The effects of flipped learning approaches in anatomy class. Sustainability 13:13724.

Hydrie MZ, Naqvi SM, Alam SN, Jafry SI. 2021. Kolb’s Learning Style Inventory 4.0 and its association with traditional and problem-based learning teaching methodologies in medical students. Pak J Med Sci 37:146–150.

Jafar S, Sittther V. 2021. Comparison of student outcomes and evaluations in hybrid versus face-to-face anatomy and physiology I courses. J Coll Sci Teach 51:58–66.

Joseph MA, Roach EJ, Natarajan J, Karkada S, Cayaban AR. 2021. Flipped classroom improves Omani nursing students performance and satisfaction in anatomy and physiology. BMC Nurs 20:1.

Kellesarian SV. 2018. Flipping the dental anatomy classroom. Dent J (Basel) 6:23.

Khan R, Phlahouras J, Johnston BC, Saffidi MA, Grover SC, Walsh CM. 2018. Virtual reality simulation training for health professions trainees in gastrointestinal endoscopy. Cochrane Database Syst Rev 8:CD008237.

Kolb DA. 1984. Experiential Learning: Experience as the Source of Learning and Development. 1st Ed. Upper Saddle River, NJ: Prentice Hall. 256 p.

Lage MJ, Platt GJ, Treglia M. 2000. Inverting the classroom: A gateway to creating an inclusive learning environment. J Econ Educ 31:30–43.

Locketz GD, Lui JT, Chan S, Salisbury K, Dort JC, Youngblood P, Blevins NH. 2017. Anatomy-specific virtual reality simulation in temporal bone dissection: Perceived utility and impact on surgeon confidence. Otolaryngol Head Neck Surg 156:1142–1149.

Logeswaran A, Munsch C, Chong YJ, Ralph N, McCrossnan J. 2021. The role of extended reality technology in healthcare education: Towards a learner-centred approach. Future Healthc J 8:e79–e84.

Losco CD, Grant WD, Armson A, Meyer AJ, Walker BF. 2017. Effective methods of teaching and learning in anatomy as a basic science: A BEME systematic review: BEME guide no. 44. Med Teach 39:234–243.

McDonald AC, Green RA, Zacharias A, Whitburn LY, Hughes DL, Logeswaran A, Munsch C, Chong YJ, Ralph N, McCrossnan J. 2021. Integration of traditional and innovative methodologies. Med Teach 39:30–43.

Meyer AJ, Stomski NJ, Losco CD, Armson AJ. 2016. The influence of anatomy app use on chiropractic students’ learning outcomes: A randomised controlled trial. Chiropr Man Therap 24:44.
Mishall PL, Meguid EM, Khalil MK, Lee LM. 2022. Transition to effective online anatomical sciences teaching and assessments in the pandemic era of COVID-19 should be evidence-based. Med Sci Educ 32:247–254.

Missildine K, Fountain R, Summers L, Gosselin K. 2013. Flipping the classroom to improve student performance and satisfaction. J Nurs Educ 52:597–599.

Mark G, Magne TA, Carstensen T, Stigen L, Åslí LA, Gramstad A, Johnson SG, Bonsaksen T. 2020. Associations between learning environment variables and students’ approaches to studying: A cross-sectional study. BMC Med Educ 20:120.

Moro C, Štromberga Z, Raikos A, Stirling A. 2017. The effectiveness of virtual and augmented reality in health sciences and medical anatomy. Anat Sci Educ 10:549–559.

Moro C, Birt J, Stromberga Z, Phelps C, Clark J, Glasziou P, Scott AM. 2021. Virtual and augmented reality enhancements to medical and science student physiology and anatomy test performance: A systematic review and meta-analysis. Anat Sci Educ 14:368–376.

Moore KL, Dalley AF II, Agur AM. 2017. Clinically Oriented Anatomy. 8th Ed. Philadelphia, PA: Wolters Kluwer. 1168 p.

Netter FH. 2018. Atlas of Human Anatomy. 7th Ed. Philadelphia, PA: Elsevier Inc. 640 p.

Ning HK, Downing K. 2010. Connections between learning experience, study behaviour and academic performance: A longitudinal study. Educ Res 52:457–468.

O’Loughlin VF, Griffith LM. 2020. Developing student metacognition through reflective writing in an upper-level undergraduate anatomy course. Anat Sci Educ 13:680–693.

Pather N, Blyth P, Chapman JA, Dayal MR, Flack NA, Fogg QA, Green RA, Hulme AK, Johnson IP, Meyer AJ, Morley JW, Shortland PJ, Štrkalj G, Štrkalj M, Valter K, Webb AL, Woodley SJ, Lazarus MD. 2020. Forced disruption of anatomy education in Australia and New Zealand: An acute response to the Covid-19 pandemic. Anat Sci Educ 13:284–300.

Pawlina W, Drake RL. 2016. Authentic learning in anatomy: A primer on pragmatism. Anat Sci Educ 9(1):5–7.

Pipitone JM, Raghavan C. 2017. Socio-spatial analysis of study abroad students’ experiences in/of place in Morocco. J Exp Educ 40:264–278.

Pringle Z, Rea PM. 2018. Do digital technologies enhance anatomical education? Pract Evid Scholarship Teach Learn High Educ 13:2–27.

Rezende AB, de Oliveira AG, Vale TC, Teixeira LA, Lima AR, Lucchetti AL, Lucchetti G, Tibirici SH, Ezequiel OS. 2020. Comparison of team-based learning versus traditional lectures in neuroanatomy: Medical student knowledge and satisfaction. Anat Sci Educ 13:591–601.

Roy H, Ray K, Saha S, Ghosal AK. 2020. A study on students’ perceptions for online Zoom-app based flipped class sessions on anatomy organized during the lockdown period of COVID-19 epoch. J Clin Diag Res 14:1–4.

Saltarelli AJ, Roseth CJ, Saltarelli WA. 2014. Human cadavers vs. multimedia simulation: A study of student learning in anatomy. Anat Sci Educ 7:331–339.

Shin M, Prasad A, Sabo G, Macnow ASR, Sheth NP, Cross MB, Premkumar A. 2022. Anatomy education in US medical schools: Before, during, and beyond COVID-19. BMC Med Educ 22:103.

Stilesc BV, Draskic M, Fasel JH. 2010. Cadaver procurement for anatomy teaching: Legislative challenges in a transition-related environment. Med Sci Law 50:45–49.

Stringer JK, Santen SA, Lee E, Rawls M, Bailey J, Richards A, Perera RA, Biskobing D. 2021. Examining Bloom’s taxonomy in multiple choice questions: Students’ approach to questions. Med Sci Educ 31:1311–1317.

Srinivasan DK. 2020. Medical students’ perceptions and an anatomy teacher’s personal experience using an e-learning platform for tutorials during the Covid-19 crisis. Anat Sci Educ 13:318–319.

Stromberga Z, Phelps C, Smith J, Moro C. 2021. Teaching with disruptive technology: The use of augmented, virtual, and mixed reality (HoloLens) for disease education. Adv Exp Med Biol 1317:147–162.

Thompson AR. 2015. The blooming anatomy tool (BAT): A discipline-specific rubric for utilizing Bloom’s taxonomy in the design and evaluation of assessments in the anatomical sciences. Anat Sci Educ 8:493–501.

Triepels CP, Smeets CF, Notten KJ, Kruitwagen RF, Futterter JJ, Vergeldt TF, Van Kuijk SM. 2020. Does three-dimensional anatomy improve student understanding? Clin Anat 33:25–33.

Uhl JF, Jorge J, Lopes DS, Campos PF (Editors). 2021. Digital Anatomy: Applications of Virtual, Mixed and Augmented Reality. 1st Ed. Cham, Switzerland: Springer Nature Switzerland AG. 399 p.

Waxman SG. 2020. Clinical Neuroanatomy. 29th Ed. New York, NY: McGraw-Hill Companies, Inc. 384 p.

Wickramasinghe NB, Thompson BR, Xiao J. 2022. The opportunities and challenges of digital anatomy for medical sciences: Narrative review. JMIR Med Educ 8:e34687.

Yang C, Yang X, Yang H, Fan Y. 2020. Flipped classroom combined with human anatomy web-based learning system shows promising effects in anatomy education. Medicine (Baltimore). 99:e23096.

Ye Z, Dun A, Jiang H, Nie C, Zhao S, Wang T, Zhai J. 2020. The role of 3D printed models in the teaching of human anatomy: A systematic review and meta-analysis. BMC Med Educ 20:335.

Yoo H, Kim D, Lee YM, Rhyu J. 2021. Adaptations in Anatomy Education during COVID-19. J Korean Med Sci 36:e13.

Yudkowsky R, Luciano C, Banerjee P, Schwartz A, Alaraj A, Lemole GM Jr, Charbel F, Smith K, Rizzi S, Byrne R, Bendok B, Frim D. 2013. Practice on an augmented reality/haptic simulator and library of virtual brains improves residents’ ability to perform a ventriculotomy. Simul Healthc 8:25–31.

Zaidi NB, Hwang C, Scott S, Stallard S, Purkiss J, Hortsch J. 2017. Climbing Bloom’s taxonomy pyramid: Lessons from a graduate histology course. Anat Sci Educ 10:456–464.

Zaidi NB, Grob KL, Monrad SM, Kurtz JB, Tai A, Ahmed AZ, Gruppen LD, Santen SA. 2018. Pushing critical thinking skills with multiple-choice questions: Does Bloom’s taxonomy work? Acad Med 93:856–859.

Zhang J, Xu X, Jiang H, Ding Y. 2020. The effectiveness of virtual reality-based technology on anatomy teaching: A meta-analysis of randomized controlled studies. BMC Med Educ 20:127.

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SUPPORTING INFORMATION
Additional supporting information can be found online in the Supporting Information section at the end of this article.

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