HoloLens and mobile augmented reality in medical and health science education: a randomised controlled trial

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Biographies

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Abstract
Due to increasing demands in the amount of content to be learned within a medical and health sciences curriculum, there are benefits towards exploring options for new and effective delivery modes. Augmented reality technology has the potential to enhance learning in physiology and anatomy, where students require a three-dimensional knowledge of human organ systems and structures. This study aimed to assess the effectiveness of learning when an identical lesson was delivered through augmented reality using either the Microsoft HoloLens or a mobile hand-held tablet device. Thirty-eight pre-clinical undergraduate participants completed a lesson detailing the physiology and anatomy of the brain. Pre- and post-intervention tests were provided to evaluate acquired knowledge. After the activity, participants also completed a Likert-style questionnaire to evaluate adverse health effects experienced and assess their perceptions of the module. There were no significant differences between test scores from lesson delivery in either the HoloLens or mobile-based augmented reality. However, a significant increase was reported in dizziness when using the HoloLens (25% higher, n=19, p=0.04). No other adverse health effects, such as nausea, disorientation or fatigue were observed. Both modes were effective for learning, providing evidence to support educators and developers wishing to adopt an augmented reality method of delivery in health sciences and medicine.

Keywords
Virtual reality; augmented reality; HoloLens; medical education; science; health education; higher education; mobile learning; randomised controlled trial.

Practitioner Notes

What is already known about this topic

- Modern technology continues to disrupt the way we teach in higher education.
- Teaching through virtual and augmented reality has shown great benefit in enhancing learning and the student experience in health sciences and medicine.
- There is the potential for new and upcoming delivery modes to continue this trend, including the introduction of both mobile and head-mounted display based augmented reality.

What this study contributes

- Investigates the potential for augmented reality to be used as a teaching tool, and supports its implementation in tertiary education.
- Identifies that although slight dizziness was reported in some participants from using the HoloLens, this does not appear to impact learning or student perceptions of the technology.
- Presents the HoloLens and mobile-based augmented reality as novel and evidence-based methods of instruction in health sciences and medicine.

Implications for practice and/or policy

- Augmented reality is an effective delivery mode which can enhance learning.
- Students consider augmented reality through both the HoloLens and mobile-based devices to be enjoyable and engaging.
- This novel method of instruction is useful to supplement learning in a tertiary education program.

Introduction

In a medical or health sciences program, the amount of information required for comprehension in physiology and anatomy courses is increasing along with dedicated time to develop clinical skills. As such, medical students are in need of effective tools that enhance their level of engagement with the learning material while promoting knowledge retention. One of the critical aspects of medical education is mastering the terminology and clinical application of human anatomy, which can be particularly challenging for many medical students in their pre-clinical years (Abu-Hijleh, 2010). However, students are often challenged with restrictions regarding the time frame in which they have hands-on lessons using a cadaver. To enhance their understanding of anatomical structures, students frequently supplement learning with cadavers with self-directed study through two-dimensional (2D) resources such as textbooks, anatomical atlases, flashcards, and lecture material. Research has shown that retention of knowledge is improved when the student is actively involved in their learning experience (Pelargos *et al.*, 2017). Learning anatomical structures is most effective in a setting where learners can quickly examine the structure from all angles, such as when using cadavers or plastic models. As such, graphic illustrations found on physical books or screens can be insufficient to aid with the students' learning journey (Moro, Stromberga, Raikos, & Stirling, 2017).

Finding ways to improve and optimise learning for the diverse range of learners in today's higher education classrooms can be challenging. Variations in the disruptive technology devices, the introduction of augmented reality, and other new modes provide a range of options for educators wishing to adopt technology-enhanced learning within their curricula. This study was guided by the research question, how does learning via mixed reality holograms compare to augmented reality-based learning in health sciences and medicine? This paper will firstly provide some background about disruptive technologies used in education. Secondly, it will present the research design and findings from the study. This will then be followed by a discussion of the findings, implications and limitations of the study.

Disruptive technologies in health and medical education

The rapid advancements in technology over the last decade has significantly impacted the way medicine and health sciences has been taught and learnt. Specifically, the release of consumergrade virtual reality (VR) and augmented reality (AR) technologies have given rise for creating innovative learning tools that can promote hands-on learning experiences (Kuehn, 2018; Cipresso, Giglioli, Raya, & Riva, 2018). Collectively, these are often considered educational 'disruptive technologies', as their introduction is poised to alter the way teaching is conducted significantly. Disruptive technologies are innovations that disrupt and displace established market leaders by offering a variety of modern services different from those currently available (Christensen, 2013; Dunning, 2019). Although disruptive technologies have the potential to replace current and routine practices in teaching and learning, many educators do find the move to novel instructional methods challenging (Liu, Geertshuis, & Grainger, 2020). However, institutions are increasingly offering support and training for academics, providing resources to support the integration of technology into curricula (Moro, Stromberga, & Birt, 2020). In addition, medical libraries have been expanding their provision of technology, making it more accessible to both students and Faculty (Herron, 2016).

Technology increasingly aids students with enhanced access to learning materials and expands the availability of information by providing learning tools for students beyond the classroom (Kuehn, 2018), and can provide dynamic and different ways to deliver content which incorporates multiple senses. In addition, there is an increasing use of these technologies beyond the tertiary environment, such as in medical training for laparoscopic surgical training, echocardiography and neurosurgical procedures (Barsom, Graafland, & Schijven, 2016). This means that utilising disruptive technologies within a medical or health science curricula may not only facilitate learning but also prepare students for a highly technology-enhanced workplace.

Virtual reality (VR) utilises a computer system or smartphone to generate a virtual environment that mimics the real world. The artificial environment that is created fully immerses the user in a visual environment, which may also include tactile and auditory sensations (Moro, Stromberga, Raikos, & Stirling, 2017). Virtual reality provides a range of interactive digital experiences through the use of a head-mounted display, and in many cases also incorporates headphones and hand-guided controls. Within this virtual world, the software can allow users to move and interact with all aspects of the environment, and fully manipulate virtual objects in any way, shape, or form.

Augmented reality (AR) projects augmented visuals to the user via optical see-through displays or see-through video displays. Most commonly, this is performed through the use ofahand-held mobile device (i.e. smartphone or tablet.). The technologyworks by overlaying computer-generated graphics or virtual objects on the user's natural setting to enhance the experience and provide a composite view (Maas, & Hughes, 2020; Rolland, & Fuchs, 2000). It is a real-world environment which is overlaid with interactive, digital elements. This enables enriched immersive experiences that were originally used for gaming, however, can also be found in early childhood education (Han, Jo, Hyun, & So, 2015), K - 12 education and in higher education (Saltan, & Arslan, 2016). It also provides a way for educators or developers to provide scaffolded learning experiences for students in a way that can allow self-paced and even problem-based learning in physiology and anatomy. This can be employed in place of formal scientific laboratories, providing particular assistance to students in the first few years of a medical program as they transition to university study (Moro, & McLean, 2017). Research exploring teaching environments that are enriched through the use of AR has shown evidence on improved student interaction, engagement, motivation, attitudes, satisfaction, and academic performance along with pedagogical affordances (Akçayır, & Akçayır, 2016; Saltan, & Arslan, 2016). Augmented reality and mixed reality are occasionally used as exclusive terms in the literature, when in practice they can often be considered synonymous. Of particular interest to many educators is the Microsoft HoloLens, a recently introduced head-mounted display which uses holographic technology to generate augmented visuals(Hoffman, 2016). These holograms can be interacted with through hand gestures or voice commands. The HoloLens falls within the augmented reality portion of the Milgram Virtuality Continuum (Milgram, & Kishino, 1994), having significant real-world elements with a smaller amount of augmented visuals. In particular, the HoloLens allows a binocular depth cue, presenting the ability to reproduce genuine 3D models, whereas mobile-based augmented reality is limited by a flat surface and can only display pseudo-3D representations of the models.

Although the use of augmented reality technology for teaching remains relatively new, benefits have already been identified from using the HoloLens for medical use, such as for visualising organs prior to surgery (Cartucho, Shapira, Ashrafian, & Giannarou, 2020), teaching dental students (Zafar, & Zachar, 2020), and in pathology education (Hanna, Ahmed, Nine, Prajapati, & Pantanowitz, 2018). However, this technology has not yet been commonly utilised in the tertiary medical or health education environments. The collaboration of the real and virtual environments in augmented reality devices should reduce the experienced adverse health effects in virtual reality applications, such as blurred vision, disorientation and cybersickness (Moro, Stromberga, Raikos, & Stirling, 2017). The precise 3D models presented in the HoloLens, as well as the hands-free nature and ability to manipulate holographic images in real space, are some of the advantages of using this technology in health science and medical education. In addition, the HoloLens has demonstrated the potential to significantly improve knowledge scores, knowledge retention, spatial awareness, as well as enjoyability in anatomical education (Brun *et al.*, 2019; Hackett, & Proctor, 2018; Mitsuno, Ueda, Hirota, & Ogino, 2019). This tool addresses the constraints of cadaver use, as well as the limitations associated with using 2D methods for teaching and learning. Learning tools for students in health science or medicine fields need to be readily available, three-dimensional and interactive for optimal engagement, which can be achieved with the integration of augmented reality technology in tertiary education. This study aimed to investigate the effectiveness of holographic technology compared to augmented reality to enhance students' knowledge on the anatomy and physiology of the brain.

Theoretical Rationale and Conceptual Framework underlying this study

The theoretical background informing the development of the learning activities created for this study stem from the Dewey (1986) theories of constructivism, learner-centred theory or student-centred learning, and experiential knowledge, all of which differ from traditional classroom learning. Although his work is centred around school classrooms, the concept has been extrapolated for use in higher education (Wright, 2011), where innovative learning can represent or replicate authentic or real-life situations and the development of in-depth knowledge (Knobloch, 2003), along with transferable skills and employability skills such as problem-solving, critical thinking and reflection (Hoidn, 2017). Learner-centred classrooms provide learners with the opportunity to construct their own meaning, as well as shared meanings, through new experiences and information and relating them to prior experiences. These ideas are particularly important in classes with diverse populations, as is represented by the participants in this study.

The modern educational environment is fast becoming integrated with the online collaborative environment, and it is common to promote engagement through technology use. Disruptive technologies provide students with the ability to be active and self-directed learners, controlling the pace of their own learning through hands-on experiences. Active learning also results in better learning outcomes evidenced by higher retention of learning (Meng *et al.*, 2019). This also aligns with Rogers (2012) perception that teaching is about facilitating learning and that all learners come with different knowledge, interests and skills, making the construction of knowledge a personal responsibility. In addition, using technology for learning allows the educator to quickly adapt, update and alter the content in a way not possible with a prescribed textbook, such as by introducing serious games, highly engaging activities (Moro, Phelps, & Stromberga, 2020), or virtualised dissection tables in place of cadaveric specimens (Nambiar, & Moro, 2019). When connected to online resources, technology-enhanced resources also enables pedagogy surrounding the connectivism learning theory (Downes, 2010; Siemens, 2004). Learners can connect to online networks and share or search for information. This approach to augmented reality lessons based around connectivism theories has already been effective in enhancing scientific literacy (Techakosit, & Wannapiroon, 2015), and presents a structure which can further enhance the learning opportunities for students.

Methods

Participants

All students enrolled in a first-year health or biomedical sciences programs at an Australian University were eligible to participate in this randomised controlled trial. Forty students aged between 17-25 volunteered after responding to advertisements posted within their lectures and a university noticeboard. After signing an informed consent form, randomisation was performed by a research assistant, who was not connected to the study, by using a software program (https://www.random.org/, Randomness and Integrity Services Ltd., Dublin, Ireland). This separated participants into two groups: a mobile-based augmented reality (AR) group and a Microsoft HoloLens group, each containing 20 participants. Of the 40 participants that were enrolled, data from two participants were excluded from the final analysis due to incomplete data (one participant from the AR group and one from the HoloLens group, $N = 38$). Neither the participants nor the study personnel were able to foresee the intervention allocation in advance to ensure allocation concealment (Figure 1). After the randomisation, all participants were handed a Samsung Galaxy Tab S3 (Samsung Electronics, Seoul, South Korea) tablet with an online Qualtrics XM (Qualtrics XM) survey loaded to ensure anonymous recording. Due to nature of the head-mounted display, it was not possible to blind participants to which group they were in after allocation. However, all responses were recorded anonymously. Blinding of the outcome assessment was completed using Qualtrics XM, and anonymised data were then exported to a spreadsheet to analyse the results. Researchers were not aware of which intervention related to which set of responses until after analysis was complete. Ethics for this study was approved by the University Human Ethics Committee and all participants were provided with an explanatory statement.

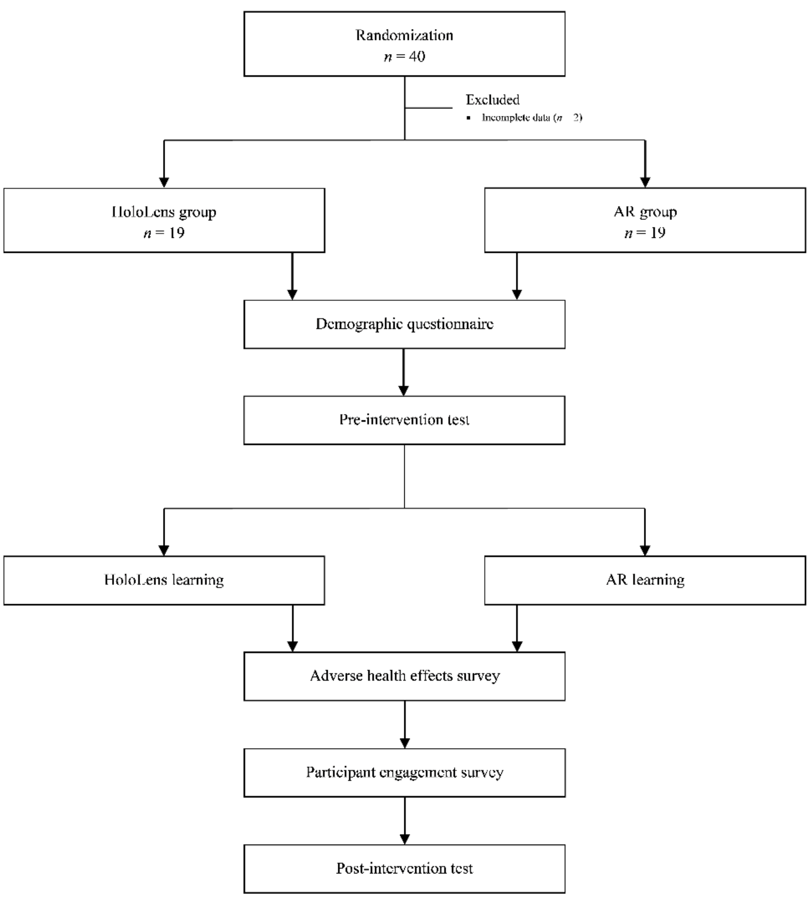

Figure 1: Flow chart detailing each of the experimental procedures and participant randomisation.

Development of the application

A lesson on brain physiology and anatomy was created in-house to be run identically on either a tablet in the mobile-based augmented reality group or the Microsoft HoloLens. All coding, model editing, exporting and lesson content utilised in this study was developed in its entirety by the first author. For both the HoloLens and mobile hand-held augmented reality devices, the lesson was developed using Unity 3D (Unity Technologies, San Francisco, California, USA) with C# coding for interactive elements. The 3D model of the brain was created using 3D Studio Max (Autodesk Inc, San Rafael, California, USA), colourised and labelled, then imported into Unity 3D. The Vuforia v5 plug-in for Unity (PTC Inc., Boston, MA) allowed visualisation using the device's camera, and all applications for the mobile-based augmented reality group used Samsung Galaxy Tab S3 (Samsung Electronics, Seoul, South Korea) tablets. For HoloLens use, all Unity files were exported through Visual Studio v2019 using the Universal Windows Platform format. For educators looking to create applications on the HoloLens, Microsoft's "Introduction to Mixed Reality Development, 2020" series of online documents contains much of the introductory instructions and content required to commence development.

The mobile-based augmented reality lesson utilised interactive 3D images of the brain and contained a six-minute audio stream narration. Participants started the application and held a marker in their hand, which appeared when placed in front of the device's camera on the screen as a model of the brain using augmented reality technology. The model could be rotated by rotating the marker in the user's hands. By tapping on the screen, specific features were highlighted, and the name displayed in text. For example, by tapping on the cerebellum, the region became highlighted and the label 'cerebellum' displayed at the base of the screen. Once a part of the brain was highlighted, the user could click a 'dissect' button to remove this feature and observe the underlying anatomy. The user clicked 'play' to commence the audio narration and start the lesson. As the audio narration progressed, relevant areas were highlighted in a different colour. When features were discussed, if an object had previously been dissected and was not visible on the screen, it was replaced and highlighted to draw the user's attention.

The HoloLens-based augmented reality lesson was identical in content, narration, and modelling to the mobile device. The brain was presented as a hologram through the head-mounted display, with the user viewing the model on the screen. No marker or hand-held object was required for anchoring the model. Participants were able to interact with the model using voice (e.g. ‘dissect’, ‘remove layer’, ‘undo’) or gesture commands in place of the buttons available on the mobile AR device (Figure 2). To highlight features, the user would hold their finger out and ‘tap’ in the air where the model was displayed. This gesture was detected by the HoloLens and the region became selected and the name displayed in text on the screen. This selected model could then also be dissected by either hand gestures or voice commands to view the underlying anatomy.

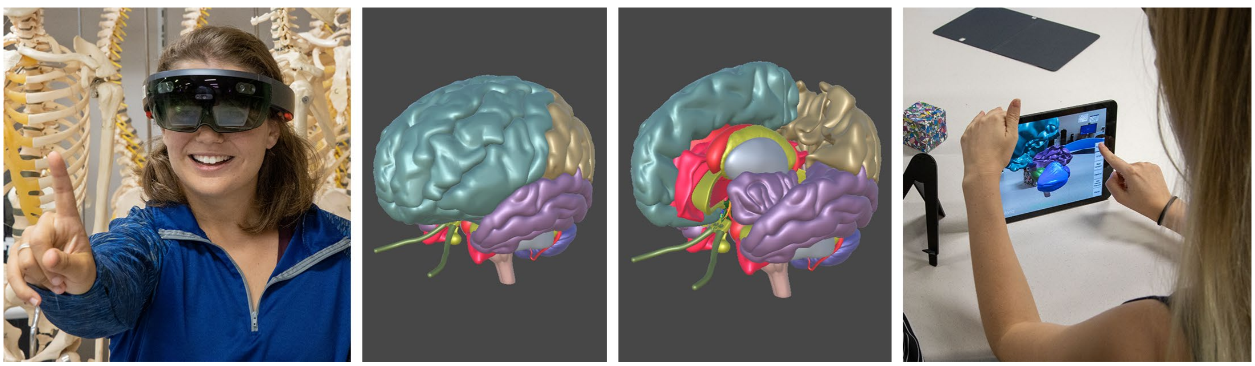

Figure 2: Images of participants using the Microsoft HoloLens (left) and Augmented Reality mobile device (right) to work through the lesson on brain physiology and anatomy, using the created model. The lesson commences as a whole brain (centre left) with the participants able to dissect and remove layers to expose the internal features (centre right) in both the HoloLens, through hand gestures or voice commands, and the augmented reality mobile device, through tapping on the respective buttons on the screen.

Research design

Both groups received brief (average of five minutes) verbal training with the research assistant on the devices and shown how to turn on and off the brain structures to ensure sufficient proficiency with the technology before the commencement of the activity. Once the user was confident in dissecting the model’s layers the formal session commenced. Initially, each participant completed the pre-intervention test, followed by commencement of the learning activity. The lesson included an interactive 3D model of the brain and a six-minute conversational, lecture-style audio-stream narrated by a specialist in the field providing an overview of the anatomy and physiology of the brain. Maintaining lessons under 10 minutes reduces dizziness or fatigue when in a virtual environment (Moro, Stromberga, Raikos, & Stirling, 2017). As different brain structures were introduced during the audio-stream, the structures in conjunction with the anatomical name of the feature would highlight in blue to capture the learner's attention. The user was able to rewind the audio-stream by five seconds, as well as pause or play when required.

We measured the following outcomes: test scores before and after the lesson; adverse health effects; and participant perceptions of the delivery mode. After the lesson participants completed two Likert-style questionnaires evaluating the adverse health effects experienced during the lesson, adapted from Ames, Wolffsohn & McBrien (2005); and participant engagement was assessed with a learning tool adapted from Hu, Wilson, Ladak, Haase & Fung (2009). The last part of the online questionnaire required the participants to complete a post-intervention test which consisted of 15 multiple-choice questions. The questions included the five questions from the pre-intervention test and 10 new questions. Before analysis, the test questions were piloted to ensure that each question could be answered using the study material provided and the data were extracted for analysis using Prism v8 Software (GraphPad Software, La Jolla, California, USA). Questions included assessments such as: 'Which part of the brain is depicted by number 3 in the image above?'; 'The somatosensory cortex is associated with which of the following?'; and 'Which of the following is not a lobe of the cerebral cortex?'.

Validation and reliability

For survey validation, an expert committee was established with six academics who had experience teaching anatomy and physiology. This committee evaluated the face value of the survey and established the validity of the questions, assessing each survey item on the relevance, clarity, format, simplicity, comprehensibility and grammatical construction. The questionnaire was administered by a research assistant who did not have a role in the teaching within any of the programs. The survey was written in a way that enabled participants to complete it in full without any further instruction after the initial training. Results from the Likert scale survey of participant perceptions returned a Cronbach's alpha of 0.775, demonstrating an acceptable internal consistency. No participants had any queries or questions for the research assistant regarding the survey after it had commenced.

Data analysis

An online questionnaire was created using Qualtrics XM (Qualtrics, Provo, UT) to record demographic data, knowledge test results, participant perceptions of their engagement and adverse effects experienced using the learning tools. The data obtained in this study were analysed using GraphPad Prism 8.3.0 (GraphPad Software, San Diego, California, USA). An unpaired Student's t-test, where $p < 0.05$ was considered statistically significant, was used to determine whether there was a statistical difference between the knowledge tests (pre- and post-test) and the mode of delivery (HoloLens or mobile-based AR). A Mann-Whitney U-test was used to evaluate the association between the mode of lesson delivery and the adverse health effects experienced during the lesson and the participant perception of the learning mode. The adverse health effects were rated on a four-point Likert scale (1 = *none* to 4 = *severe*), where lower scores were associated with fewer symptoms experienced. Participant perception of the learning tool was rated using a five-point Likert scale (1 = *strongly disagree* to 5 = *strongly agree*), where higher scores indicated a positive perception about the learning mode.

Results

This section of the paper will present the results, including a summary of the participants, the results of the knowledge test scores, indicators of adverse health effects and participant engagement with the devices.

Participants

A total of 18% of participants recruited in this study had some recall of the anatomical structures associated with the brain, 57% had previously studied brain anatomy but could not recall the anatomical features, and 32% had never studied the anatomy of the brain. Prior experience with using modern 3D visualisation technology (i.e. VR, AR, 3D glasses) was reported by 45% of the participants (Table 1). There were no significant differences between the groups.

Table 1: Participant information.

Characteristics	Tablet-based AR (n = 19)	HoloLens (n = 19)	Total (n = 38)
Recall the anatomy, % (n)	26% (5)	10% (2)	18% (7)
Previously studied anatomy (cannot recall anatomy), % (n)	47% (9)	68% (13)	57% (22)
Never studied anatomy, % (n)	31% (6)	37% (6)	32% (12)
Prior experience with VR/AR/3D glasses, % (n)	37% (7)	53% (10)	45% (17)

Knowledge Test Scores

A five-item knowledge pre-test was administered to all participants prior to intervention to obtain baseline data. The results from the pre-test showed that the baseline knowledge scores for both groups were not significantly different (p = NSD). Out of five possible marks achievable in the pre-test, the mobile-based AR application group achieved a mean score of 3.84 ± 1.54, and the HoloLens group had a score of 4.16 ± 1.21 (Table 2). After completing the anatomy and physiology brain lesson, out of 15 possible marks achievable in the post-test, the AR group received a mean score of 11.05 ± 3.75 and the HoloLens group 11.89 ± 2.16. There was no significant difference observed in the anatomical test scores between the two groups (p = 0.69).

Table 2: Pre-intervention and post-intervention test knowledge scores for the tablet-based AR application and the HoloLens groups. Data reported as mean score (SD) with a significance level of $p < 0.05$.

Knowledge test	Tablet-based AR ($n = 19$)	HoloLens ($n = 19$)	p value ($n = 38$)
Pre-test (/5)	3.84 (1.54)	4.16 (1.21)	0.69
Post-test (/15)	11.05 (3.75)	11.89 (2.16)	0.69
New questions (/10)	6.89 (2.62)	7.31 (1.53)	0.88
Pre-test questions (/5)	4.16 (1.43)	4.58 (1.07)	0.14

Adverse Health Effects

The HoloLens group reported a significantly higher experience rating of the symptom dizziness throughout the lesson, compared to the mobile-based AR application group ($p = 0.04$, Table 3). There were no significant differences in the other symptoms experienced between both groups.

Table 3: Percentage of students that exhibited adverse health effects during the brain anatomy lesson on the tablet-based AR application and the HoloLens.

Symptoms	**Tablet-based AR (*n = 19*)**	**HoloLens (*n = 19*)**	***p* value (*n = 38*)**
General symptoms			
General discomfort	10%	35%	0.12
Fatigue	10%	20%	0.99
Drowsiness	5%	5%	0.99
Headache	0%	15%	0.23
Dizziness	0%	25%	0.04*
Difficulty concentrating	25%	30%	0.99
Nausea	0%	5%	0.99
Disorientation	5%	5%	0.99
Eye-related symptoms			
Eyestrain	15%	25%	0.40
Blurred vision	5%	15%	0.60
Difficulty focusing	20%	25%	0.99
Double-vision	0%	5%	0.99

*$p < 0.05$

Participant Engagement with the Learning Mode

Participants rated their learning experience using each learning tool on a 5-point Likert scale in response to the given statements. The reported learning experience was rated highly across all eight of the domains for both groups (Figure 3). The HoloLens group reported a significantly higher enjoyability mean score for the statement 'The instructions and labels were clear' compared to the mobile-based AR group ($p = 0.02$, Table 4). There were no significant differences in mean scores for other participant perceptions between the two learning tools.

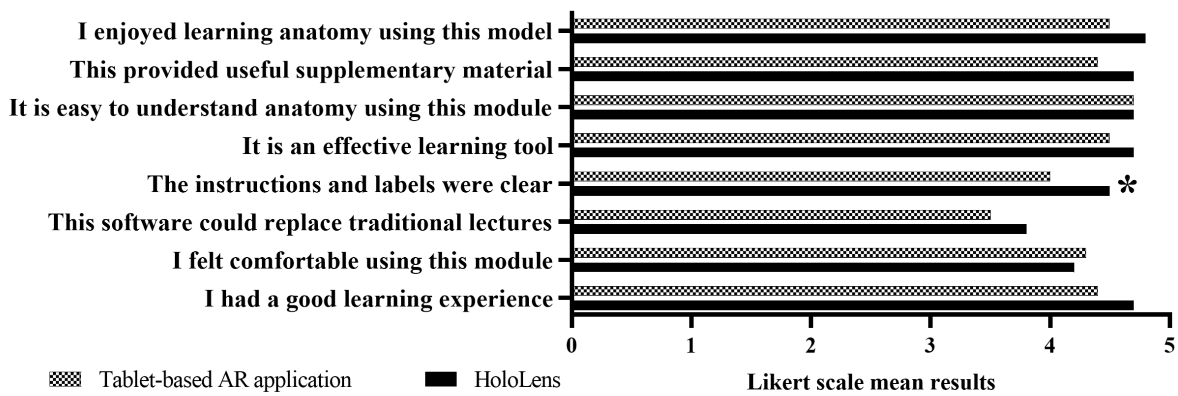

Figure 3: Participant perceptions of learning the anatomy and physiology of the brain using the mobile-based AR application and the HoloLens. Data is reported on a 5-point Likert scale (1 = *strongly disagree*, 5 = *strongly agree*). *$p = 0.02$

Discussion

Knowledge acquisition

The study aimed to determine whether learning the anatomy and physiology of the brain using the HoloLens approach was more effective than using a mobile-based augmented reality application. The results reported from this study shows that health sciences students who learned using the HoloLens performed equally well on an anatomy knowledge test as the students using the AR application. Augmented reality has been supported as an effective learning tool in anatomical education when compared to virtual reality and mobile-based instructional methods (Moro, Stromberga, Raikos, & Stirling, 2017; Tang, Cheng, Mi, & Greenberg, 2020). Therefore, the knowledge acquisition reported in both HoloLens and AR groups in this study is promising to its potential as an effective supplementary tool for anatomical education. Incorporating technology into health science and medical education is essential for knowledge acquisition in these disciplines where learning is predominantly experimental, active and self-directed. The improvement in knowledge scores using 3D technology devices can be attributed to the cognitive efficiency, shown in previous studies by a reported decrease in the cognitive load of students compared to the mental capacity required to visually manipulate 2D images (Hackett, & Proctor, 2018).

Besides the knowledge acquisition from test scores, there is the potential for learners to have a greater real-world understanding of medical concepts through the use of augmented reality (Kamphuis, Barsom, Schijven, & Christoph, 2014). Compared to textbook readings or lecture-based instructions, in medical education augmented reality has the potential to provide a heightened understanding of the structures and functions of human organs in 3D space, while providing a more realistic representation of the human body compared to traditional media (Sutherland *et al.*, 2019; Tang, Cheng, Mi, & Greenberg, 2020). Although real-world medical skills were not assessed in this current study, the potential for additional learning from technology outside of direct exam-based performance presents an interesting avenue for future research.

The general perception of MR and AR delivery

Student engagement in the education environment is increasingly defined as a characteristic of high-quality teaching and learning. As a result, many educators have recently made the shift from traditional lectures and tutorials in tertiary education to more self-paced, visual methods of learning (Birt, Stromberga, Cowling, & Moro, 2018). Incorporating augmented reality devices as teaching and learning tools presents a potential to enhance the overall learning experience. Participants reported that both learning tools provided a good learning experience, and it was easy to understand the content. However, the participants did not respond as highly to the thought of these tools replacing traditional lectures. As such, it appears that the use of augmented reality could act as a useful supplementary tool to accompany current teaching methods. When students are engaged by participating in active learning teaching approaches, there are reported benefits to student success and motivation (Pirker, Riffnaller-Schiefer, Tomes, & Gütl, 2016).

Adverse health effects as consideration for educators

One of the primary issues with implementing technology into the learning environment is cybersickness, which results in experiencing symptoms such as nausea, fatigue, difficulty concentrating, as well as problems with vision. Studies have reported that cybersickness, in particular, is increasingly exhibited when using virtual reality devices compared to mobile-based AR applications (Moro, Stromberga, & Stirling, 2017). In the current study, the participants in the HoloLens group reported higher levels of general discomfort, fatigue, headache, dizziness, difficulty concentrating, and eye-related symptoms. Of these adverse health effects, the HoloLens group reported a significantly higher rating for dizziness compared to mobile AR. Increased levels of self-reported dizziness with high standard deviation have also been noted in the literature, where Wang, Daniel, Asil, Khwaounjoo & Cakmak (2020) reported a weak, albeit significant relationship between dizziness and performance in the anatomical knowledge tests. The authors suggested that vergence-accommodation conflict may be a contributing factor to diminish performance in knowledge tests. Specifically, 3D visualisation technologies have been shown to cause this vergence-accommodation conflict which results from mismatched cues about the distance of a virtual 3D model and the focusing distance required for the eye to focus on the object, resulting in hindered visual performance and visual fatigue (Hoffman, Girshick, Akeley, & Banks, 2008). Similar concerns have been associated with the use of immersive virtual reality devices, where a sensory mismatch occurs between the visual and vestibular system (Howarth, & Costello, 1997). Experiencing increased levels of dizziness and general discomfort when using the HoloLens is of concern to the impact this may place on the overall learning quality and enjoyability.

Implications, limitations, and future studies

Facilitating effective learning and teaching within technology-enabled classrooms can be messy and complex. The learning curve for educators can be prohibitive, with not all educators ready to uptake such advanced technologies (Liu, Geertshuis, & Grainger, 2020). Several implications should be considered when incorporating augmented reality via the HoloLens, mobile devices or other disruptive technologies into the classroom environment. The finding that some students find the technology makes them dizzy means that some learners may miss out on learning objectives or aims if they cannot tolerate the devices well. There may also be challenges scaling-up the technology for large classes, as each device can be quite expensive. Another consideration is to scale this to larger cohorts, as students may need to install the software on their own smartphones or devices, which may not be ideal for all. In addition, due to the wide variety available, some models of device used by students may not be able to run the augmented reality applications. Moreover, augmented reality can be run on smartphones or tablets, whereas the Microsoft HoloLens is a standalone and expensive device, which is not yet available for consumer purchase.

The primary limitation of this study is related to the generalisation of these results due to the small sample size, where the participants came from one medical course within one university in Australia. Future studies could incorporate an assessment after a determined number of weeks to see if either mode was more effective at generating longer-term memory than the immediate recall assessed in this study. In addition, assessing the impact of these technologies in other courses or disciplines, outside of health, would be useful in identifying the overall usefulness of augmented reality in teaching and learning. Finally, it could be helpful to assess more than assessment results and self-reported perceptions, such as cognitive load, non-verbal communication (via a video), engagement or other measures to see any other benefits or considerations from these devices.

Conclusion

This study provides evidence-based support for educators wishing to incorporate augmented reality modes of instruction into their content delivery. In particular, as an emerging stereoscopic technology capable of displaying models in true 3D, the HoloLens may become an important addition to the health sciences and medical educator's choice of teaching modes in physiology and anatomy. Two-dimensional images presented in textbooks do not portray organ systems in 3D space, limiting the ability of learners to gain a spatial awareness of the human body's complex physiological and anatomical structures. The additional fact that cadavers are becoming increasingly less available due to ethical, financial, and supervisory constraints provides support for the introduction of augmented reality as a delivery mode. Test results improved for participants using both the HoloLens and mobile-based AR devices, demonstrating a potential for augmented reality to effectively enhance content delivery. Participants also enjoyed learning through both devices, presenting this enjoyable and engaging technology as a novel method of instruction. It is recommended that learning through augmented reality be utilised as a supplement to traditional methods of teaching rather than an overall replacement for the provision of course content.

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Statements on open data, ethics and conflict of interest

The data is not stored online, but is available on reasonable request by emailing the corresponding author. Ethics was approved from the Bond University Human Research Ethics Committee, Bond University, Australia. All study authors declare no conflict of interest in any aspects of this work.

Submission declaration and verification

This work has not been published previously, and it is not under consideration for publication elsewhere.

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References

Abu-Hijleh, M. F. (2010). The place of anatomy in medical education: Guide Supplement 41.1 – Viewpoint. *Medical Teacher,* **32***,* 601-603.

Akçayır, M. & Akçayır, G. (2016). Advantages and challenges associated with augmented reality for education: a systematic review of the literature. *Elsevier: Educational Research Review,* **20***,* 1-11.

Ames, S. L., Wolffsohn, J. S. & McBrien, N. A. (2005). The development of a symptom questionnaire for assessing virtual reality viewing using a head-mounted display. *Optometry and Vision Science,* **82***,* 168-176.

Barsom, E. Z., Graafland, M. & Schijven, M. P. (2016). Systematic review on the effectiveness of augmented reality applications in medical training. *Surgical Endoscopy,* **30***,* 4174-4183.

Birt, J., Stromberga, Z., Cowling, M. & Moro, C. (2018). Mobile Mixed Reality for Experiential Learning and Simulation in Medical and Health Sciences Education. *Information,* **9***,* 31.

Brun, H., Bugge, R. A. B., Suther, L. K. R., Birkeland, S., Kumar, R., Pelanis, E. & Elle, O. J. (2019). Mixed reality holograms for heart surgery planning: first user experience in congenital heart disease. *European Heart Journal Cardiovascular Imaging,* **20***,* 883-888.

Cartucho, J., Shapira, D., Ashrafian, H. & Giannarou, S. (2020). Multimodal mixed reality visualisation for intraoperative surgical guidance. *International Journal of Computer Assisted Radiology and Surgery,* **15***,* 819-826.

Christensen, C. M. (2013) *The innovator's dilemma: when new technologies cause great firms to fail*. Brighton, MA: Harvard Business Review Press.

Cipresso, P., Giglioli, I. A. C., Raya, M. A. & Riva, G. (2018). The Past, Present, and Future of Virtual and Augmented Reality Research: A Network and Cluster Analysis of the Literature. *Frontiers in Psychology,* **9***,* 2086-2086.

Dewey, J. (1986). Experience and Education. *The Educational Forum,* **50***,* 241-252.

Downes, S. (2010). New Technology Supporting Informal Learning. *Journal of Emerging Technologies in Web Intelligence,* **2***,* 27-33.

Dunning, J. (2019). Disruptive technology will transform what we think of as robotic surgery in under ten years. *Annals of Cardiothoracic Surgery,* **8***,* 274-278.

Hackett, M. & Proctor, M. (2018). The effect of autostereoscopic holograms on anatomical knowledge: a randomised trial. *Medical Education,* **52***,* 1147-1155.

Han, J., Jo, M., Hyun, E. & So, H.-j. (2015). Examining young children's perception toward augmented reality-infused dramatic play. *Educational Technology Research and Development,* **63***,* 455-474.

Hanna, M. G., Ahmed, I., Nine, J., Prajapati, S. & Pantanowitz, L. (2018). Augmented Reality Technology Using Microsoft HoloLens in Anatomic Pathology. *Archives of Pathology Laboratory Medicine,* **142***,* 638-644.

Herron, J. (2016). Augmented Reality in Medical Education and Training. *Journal of Electronic Resources in Medical Libraries,* **13***,* 51-55.

Hoffman, D. M., Girshick, A. R., Akeley, K. & Banks, M. S. (2008). Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of vision,* **8***,* 1-30.

Hoffman, M. A. (2016). Microsoft Hololens Development Edition. *Science,* **353***,* 876-876.

Hoidn, S. (2017) *Student-centred learning environments in higher education classrooms* (978-971). New York, NY: Palgrave Macmillan.

Howarth, P. A. & Costello, P. J. (1997). The occurrence of virtual simulation sickness symptoms when an HMD was used as a personal viewing system. *Displays,* **18***,* 107-116.

Hu, A., Wilson, T., Ladak, H., Haase, P. & Fung, K. (2009). Three-dimensional educational computer model of the larynx: voicing a new direction. *Otolaryngology - Head & Neck Surgery,* **135***,* 677-681.

Kamphuis, C., Barsom, E., Schijven, M. & Christoph, N. (2014). Augmented reality in medical education? *Perspectives on Medical Education,* **3***,* 300-311.

Knobloch, N. A. (2003). Is experiential learning authentic? *Journal of Agricultural Education,* **44***,* 22-34.

Kuehn, B. M. (2018). Virtual and Augmented Reality Put a Twist on Medical Education. *Journal of the American Medical Association,* **319***,* 756-758.

Liu, Q., Geertshuis, S. & Grainger, R. (2020). Understanding academics' adoption of learning technologies: A systematic review. *Computers & Education,* **151***,* Article 103857.

Maas, M. J. & Hughes, J. M. (2020). Virtual, augmented and mixed reality in K–12 education: a review of the literature. *Technology, Pedagogy and Education,* **29***,* 231-249.

Meng, X., Yang, L., Sun, H., Du, X., Yang, B. & Guo, H. (2019). Using a Novel Student-centered Teaching Method to Improve Pharmacy Student Learning. *American Journal of Pharmaceutical Education,* **83***,* 6505.

Milgram, P. & Kishino, F. (1994). A Taxonomy of Mixed Reality Visual Displays. *IEICE Transactions on Information and Systems,* **E77-D***,* 1321-1329.

Mitsuno, D., Ueda, K., Hirota, Y. & Ogino, M. (2019). Effective Application of Mixed Reality Device HoloLens: Simple Manual Alignment of Surgical Field and Holograms. *Plastic and Reconstructive Surgery,* **143***,* 647-651.

Moro, C. & McLean, M. (2017). Supporting Students' Transition to University and Problem-Based Learning. *Medical Science Educator,* **27***,* 353-361.

Moro, C., Phelps, C. & Stromberga, Z. (2020). Utilizing serious games for physiology and anatomy learning and revision. *Advances in Physiology Education,* **44***,* 505-507.

Moro, C., Stromberga, Z. & Birt, J. (2020) Technology considerations in health professions and clinical education. In Nestel, D., Reedy, G., McKenna, L. & Gough, S. (Eds.), *Clinical Education for the Health Professions: Theory and Practice.* (pp. 25). Clinical Education for the Health Professions: Theory and Practice, Springer.

Moro, C., Stromberga, Z., Raikos, A. & Stirling, A. (2017). The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education,* **10***,* 549-559.

Moro, C., Stromberga, Z. & Stirling, A. (2017). Virtualisation devices for student learning: Comparison between desktop-based (Oculus Rift) and mobile-based (Gear VR) virtual reality in medical and health science education. *Australasian Journal of Educational Technology,* **33***,* 1-10.

Nambiar, S. & Moro, C. (2019). Applied Learning of Anatomy and Physiology: Virtual Dissection Tables within Medical and Health Sciences Education. *Bangkok Medical Journal,* **15***,* 121-127.

Pelargos, P. E., Nagasawa, D. T., Lagman, C., Tenn, S., Demos, J. V., Lee, S. J., Bui, T. T., Barnette, N. E., Bhatt, N. S. & Ung, N. (2017). Utilizing virtual and augmented reality for educational and clinical enhancements in neurosurgery. *Journal of Clinical Neuroscience,* **35***,* 1-4.

Pirker, J., Riffnaller-Schiefer, M., Tomes, L. M. & Gütl, C. (2016) Motivational Active Learning in Blended and Virtual Learning Scenarios: Engaging Students in Digital Learning. In Margarida, M. P. & Dora, S. (Eds.), *Handbook of Research on Engaging Digital Natives in Higher Education Settings.* (pp. 416-437). Hershey, PA, USA, IGI Global.

Rogers, C. (2012) *Client Centred Therapy (New Ed)*. Hachette UK: Constable.

Rolland, J. P. & Fuchs, H. (2000). Optical Versus Video See-Through Head-Mounted Displays in Medical Visualization. *Presence,* **9***,* 287-309.

Saltan, F. & Arslan, Ö. (2016). The use of augmented reality in formal education: A scoping review. *Eurasia Journal of Mathematics, Science and Technology Education,* **13***,* 503-520.

Siemens, G. (2004). Connectivism: A Learning Theory for the Digital Age. *International Journal of Instructional Technology and Distance Learning,* **2**.

Sutherland, J., Belec, J., Sheikh, A., Chepelev, L., Althobaity, W., Chow, B. J. W., Mitsouras, D., Christensen, A., Rybicki, F. J. & La Russa, D. J. (2019). Applying Modern Virtual and Augmented Reality Technologies to Medical Images and Models. *Journal of Digital Imaging,* **32***,* 38-53.

Tang, K. S., Cheng, D. L., Mi, E. & Greenberg, P. B. (2020). Augmented reality in medical education: a systematic review. *Canadian Medical Education Journal,* **11***,* e81-e96.

Techakosit, S. & Wannapiroon, P. (2015). Connectivism Learning Environment in Augmented Reality Science Laboratory to Enhance Scientific Literacy. *Procedia - Social and Behavioral Sciences,* **174***,* 2108-2115.

Wang, C., Daniel, B. K., Asil, M., Khwaounjoo, P. & Cakmak, Y. O. (2020). A Randomised Control Trial and Comparative Analysis of Multi-Dimensional Learning Tools in Anatomy. *Scientific Reports,* **10***,* 6120.

Wright, G. B. (2011). Student-centered learning in higher education. *International Journal of Teaching and Learning in Higher Education,* **23***,* 92-97.

Zafar, S. & Zachar, J. J. (2020). Evaluation of HoloHuman augmented reality application as a novel educational tool in dentistry. *European Journal of Dental Education,* **24***,* 259-265.