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The Effectiveness of Collaborative Augmented Reality in Gross Anatomy Teaching: A Quantitative and Qualitative Pilot Study

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In the context of gross anatomy education, novel augmented reality (AR) systems have the potential to serve as complementary pedagogical tools and facilitate interactive, student-centered learning. However, there is a lack of AR systems that enable multiple students to engage in collaborative, team-based learning environments. This article presents the results of a pilot study in which first-year medical students (n = 16) had the opportunity to work with such a collaborative AR system during a full-day gross anatomy seminar. Student performance in an anatomy knowledge test, conducted after an extensive group learning session, increased significantly compared to a pre-test in both the experimental group working with the collaborative AR system ($P < 0.01$) and in the control group working with traditional anatomy atlases and three-dimensional (3D) models ($P < 0.01$). However, no significant differences were found between the test results of both groups. While the experienced mental effort during the collaborative learning session was considered rather high (5.13 ± 2.45 on a seven-point Likert scale), both qualitative and quantitative feedback during a survey as well as the results of a System Usability Scale (SUS) questionnaire (80.00 ± 13.90) outlined the potential of the collaborative AR system for increasing students' 3D understanding of topographic anatomy and its advantages over comparable AR systems for single-user experiences. Overall, these outcomes show that collaborative AR systems such as the one evaluated within this work stimulate interactive, student-centered learning in teams and have the potential to become an integral part of a modern, multi-modal anatomy curriculum. Anat Sci Educ 0: 1–15. © 2020 The Authors. Anatomical Sciences Education published by Wiley Periodicals LLC on behalf of American Association of Anatomy.

Key words: Gross anatomy education; undergraduate education; spatial understanding; team-based learning; augmented reality; assessment; outcomes; novel teaching modalities

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INTRODUCTION

Andreas Vesalius, a well-known physician and anatomist from the 16th century, is often referred to as the founder of modern human anatomy as he initiated one of the most important paradigm shifts in the history of anatomy by switching the focus from predominantly theoretical studies toward direct, hands-on observations of the human body through cadaveric dissections. In today's time, another paradigm shift can be experienced in the context of gross anatomy education that is characterized by the increasing use of novel anatomy learning tools that allow students to freely explore three-dimensional (3D) models of anatomical structures. One particular technology that is increasingly used in anatomy education is augmented reality (AR). The goal of AR is to seamlessly fuse virtual content with the real world (Azuma, 1997; Azuma et al., 2001), enabling students to engage in interactive and collaborative learning environments that feature 3D content (Bacca et al., 2014; Billinghurst et al., 2015; Akçayır and Akçayır, 2017). In the context of anatomy learning, AR technology encourages a transition from passive, teacher-centered and delivery-based learning toward interactive, student-centered and exploratory learning that emphasizes the hands-on character of anatomy learning and enables multiple students to engage in collaborative, team-based learning environments (Cheng and Tsai, 2013; Diegmann et al., 2015; Akçayır and Akçayır, 2017). Traditional teaching paradigms such as lectures, anatomy textbooks, and dissection courses all have very unique benefits and will not be replaced any time soon. Especially dissection courses are considered by students as an indispensable part of the undergraduate medical curriculum (Korf et al., 2008), despite attempts to use virtual dissection tables as a replacement (Anand and Singel, 2014; Paech et al., 2017, 2018; Fyfe et al., 2018). However, these traditional paradigms will be increasingly supplemented and enhanced within the next decade by novel tools that leverage the potential of AR (Kamphuis et al., 2014; Delello et al., 2015).

Background

Novel technologies for presenting 3D anatomical content to students have been recognized as an effective avenue for improving medical education environments in a large body of previously published research. Besides AR, several systems have been proposed that employ Virtual Reality (VR) or advanced stereoscopic 3D visualizations that recreate a sense of depth on a 2-dimensional (2D) screen.

Stereoscopic 3D visualization. Hackett and Proctor (2016) reviewed a total of 38 systems employing stereoscopic viewing and found that the majority of studies reported a positive impact on the understanding of anatomical structures. They also compared the use of autostereoscopic displays with monoscopic 3D visualizations in the form of 3D PDFs and regular 2D printed images for cardiac anatomy learning (Hackett and Proctor, 2018). While significant knowledge improvements were measured, 3D misperceptions, which can lead to visual discomfort and visual fatigue, were mentioned as well, therefore, the benefits remain disputed in the context of anatomy teaching (Tourancheau et al., 2012, John et al., 2016; Hackett and Proctor, 2018). In addition to these conflicting effects on learning outcome and the perceptual challenges, one of the main disadvantages of stereoscopic displays is the limited potential for collaboration.

Virtual reality. Virtual Reality systems, on the contrary, fully immerse all of the user's senses in a simulated virtual world that often aims to mimic properties of the real world. Virtual reality systems normally require expensive hardware in the form of dedicated VR work stations and head-mounted displays (HMDs). Recently, low-cost HMDs such as Google Cardboard (Google LLC., Mountain View, CA) or Samsung Gear VR (Samsung, Seoul, South Korea) have been developed that leverage the power of smartphones both as a compute and display device. Additionally, untethered consumer VR devices such as the Oculus Quest (Facebook, Menlo Park, CA) start to emerge that remove the need for an additional workstation. The use of VR in anatomy education is generally associated with a higher motivation of students for the topics of interest (Pan et al., 2006; Lee and Wong, 2008; Huang et al., 2010; Battulga et al., 2012), better spatial understanding (Lee and Wong, 2014), an increased involvement and engagement through various interaction paradigms (Chittano and Ranon, 2007), as well as increased levels of curiosity that correspond with students spending more time with VR systems compared to traditional 2D methods (Foo et al., 2013). Preim and Saalfeld (2018) discuss a series of immersive VR solutions in the context of virtual anatomy education. Several VR systems have been proposed for very specific anatomical topics, including the nasal cavity (Marks et al., 2017), the inner ear (Adams et al., 2019), cardiac anatomy (Maresky et al., 2018), and even for canine anatomy (Seo et al., 2017). In contrast to previously discussed 3D visualization techniques, VR systems inherently allow for collaborative anatomy learning, either in the form of co-located or remote collaboration (Billinghurst and Kato, 1999). However, very few studies have followed this research path and explored the potential of collaborative VR systems in the context of anatomy education. Fairén González et al. (2017) compared two VR systems, a VR powerwall and a VR cave, for anatomy learning in small groups of nursing students. The study promised a first step toward collaborative VR, but unfortunately the system was limited to only one active user, while all other co-located students only passively followed the learning experience. Another recent study investigated the use of low-cost Google Cardboard VR which allowed multiple observers to see the same virtual 3D organ models obtained from clinical cases to enable shared understanding of the anatomy (Masuoka et al., 2019). The main limitations of the system included motion sickness and eye fatigue as well as hardware problems. Despite the remaining challenges, VR does have potential for enhancing anatomy learning environments and future studies should focus both on the collaborative aspect as well as the effectiveness of immersive and interactive forms of VR (Kyaw et al., 2019).

Augmented reality. In contrast to VR, augmented reality (AR) aims to enhance the perception of the real world by incorporating virtual content in real-time that appears to coexist in the same space (Azuma, 1997; Azuma et al., 2001). There are three main categories of AR systems that can be distinguished on the basis of how the fused content is displayed to the user: handheld displays, spatial displays, and head-attached displays (Bimber and Raskar, 2006).

Handheld AR systems typically superimpose virtual content onto the live camera stream of a mobile device such as a smartphone or tablet, which combine computational power, a display, as well as interaction technology in one single device. Several handheld AR systems have been proposed for various areas of medical education, including neuroanatomy (Cook et al., 2019; Henssen et al., 2020), the anatomy of the musculoskeletal system (Chien et al., 2010; Jamali et al., 2015), the pelvis (Dixit et al., 2019), as well as for general anatomical education (Küçük et al., 2016; Wang et al., 2016; Jain et al., 2017; Kurniawan et al., 2018; Khalid et al., 2019). Recently, Moro et al. (2017) presented a comparative study that investigated the impact of a mobile AR system in comparison to VR and tablet-based systems on anatomy learning outcome. While no significant differences between these modalities could be measured, they learned that AR can be used effectively to supplement existing teaching modalities and at the same time increase the motivation and engagement of students. Similar results in terms of increased motivation, fun, and engagement were found by Birt et al. (2018), who compared a tablet-based AR system to a VR system for both learning neuroanatomy as well as acquiring procedural knowledge during laryngoscopies. While previous research has demonstrated that these systems can be integrated effectively into an educational environment for anatomy learning, handheld mobile AR solutions come with several disadvantages, including restricted interaction possibilities and limited screen sizes. Furthermore, another major disadvantage of such systems is that hands-free working is not possible.

In contrast to handheld AR systems, spatial displays (especially screen-based AR systems) show the view of a video camera with additional content on a regular monitor. Several screen-based AR systems have been proposed in the literature for the purpose of supporting anatomy education. One of them is the AR Magic Mirror, which enables users to interactively explore both anatomical structures as well as radiological section images in relation to their own body by using human pose estimation and real-time skeletal animation for superimposing virtual models of 3D organs on top of the user (Blum et al., 2012; Ma et al., 2013). The system employs advanced perceptual visualization concepts to provide a very realistic view inside the body (Ma et al., 2016a,b; Bork et al., 2017a,b). Kugelmann et al. (2018) and Bork et al. (2019a) demonstrated the systems' additional value for integrated radiology teaching in gross anatomy. Similar screen-based AR systems have been proposed by several others groups (Bauer et al., 2017; Manrique-Juan et al., 2017; Lao et al., 2019). In contrast to the AR Magic Mirror, all of these systems suffer from poor depth perception of the virtual anatomical content and a phenomenon known as *the floating effect*. This occurs when a simplistic superimposition of the 3D models is used such that the virtual content appears to be floating on top of the user. While screen-based AR systems are generally very cost effective due to the usage of standard hardware components such as a camera and a display device, common disadvantages include—similar to handheld AR systems—the limited and only indirect user interaction as well as the fact that such systems merely provide a remote viewing rather than a see-through metaphor. Furthermore, multi-user collaboration can be challenging due to the limited interaction space.

Besides handheld and spatial displays, optical see-through HMDs (the most important representative of head-attached displays) employ a combination of optical combiners and microdisplays to render a virtual image in front of the users' eyes. In recent years, this category became very prominent due to advances in HMD technology and the introduction of several commercial products, including the Microsoft HoloLens (Microsoft, Redmond, WA) and the Magic Leap One (Magic Leap, Plantation, FL). This has led to a series of works that evaluated the potential of such systems in various disciplines of medical education (Hanna et al., 2018; Holman et al., 2019; Michalski et al., 2019). The Case Western Reserve University and the Cleveland Clinic developed the HoloAnatomy app, which allowed students to study a highly detailed 3D anatomy model on the HoloLens (Workman, 2018). In addition to that, several commercial applications for anatomy learning have been introduced, including HoloHuman by Pearson (Pearson PLC., London, UK) and 3D4Medical (3D4Medical, Dublin, Ireland) for the HoloLens as well as Medivis (Medivis, Inc., Brooklyn, NY) for the Magic Leap One. HoloHuman was evaluated in a recent study by Zafar and Zacher (2020), who assessed the potential of the application for learning head and neck anatomy compared to traditional cadaver learning and found that the system provides additional value to dental students in terms of understanding of 3D anatomy. A common limitation of both academic and commercially available HMD-based AR systems is the lack for collaboration. All previously mentioned works focus on a single-user scenario in which only a single student is able to see the digital content through the AR glasses. However, team-based anatomy learning constitutes an essential learning paradigm for many medical students today and has been shown to have a positive effect on students' learning outcome, both in small groups of students (Nieder et al., 2005; Vasan et al., 2009; Vasan et al., 2011; Huitt et al., 2015) and in near-peer teaching scenarios (Evans and Cuffe, 2009; Naeger et al., 2013; Nelson et al., 2013; Owen and Ward-Smith, 2014). To fill this research gap, the VesARlius AR system for the Microsoft HoloLens (Bork et al., 2019b). A thorough search of the relevant literature yielded that VesARlius to date is the only HMD-based AR system that enables teams of co-located students to engage in a collaborative anatomy learning environment, both in the context of student–student and student–teacher interactions.

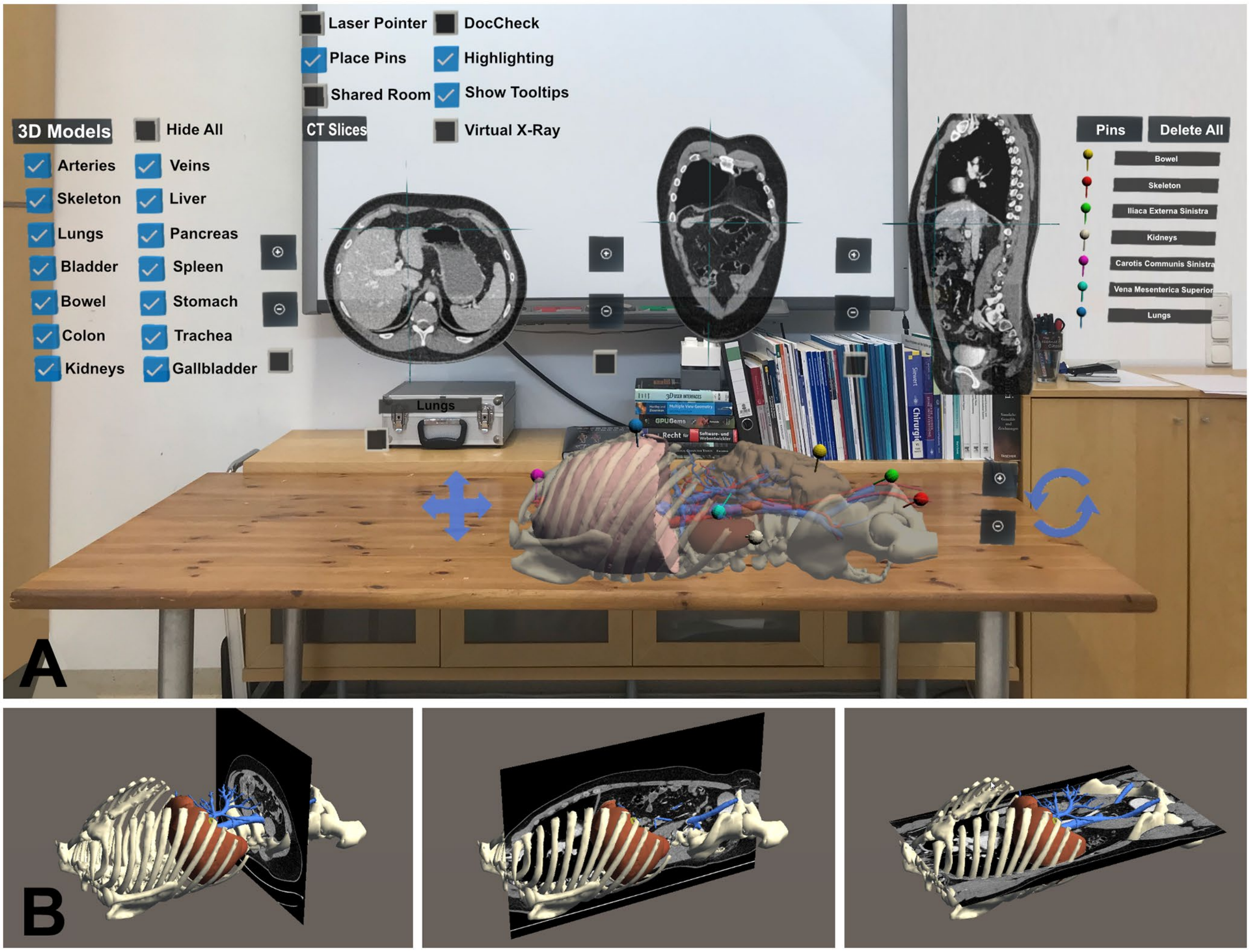
Contributions

The present study aims to determine the effectiveness and potential of AR-based anatomy learning with the VesARlius system in terms of learning outcomes in a collaborative setting. A detailed description of the systems' features is provided, specifically of those that enable collaboration between multiple students. During an experimental user study with 16 first-year medical students, the potential of VesARlius for serving as an additional teaching modality in the context of both topographic anatomy as well as radiology learning was investigated. Differences in learning outcome between a group of students learning with VesARlius and a control group learning with traditional anatomy textbooks and 3D models were measured. In conjunction with previous research that introduced such novel AR systems into the medical curriculum, it was hypothesized that learning with VesARlius not only provides an equivalent or better learning outcome compared to traditional learning with anatomy textbooks and 3D models, but also improves 3D understanding of topographic anatomy according to students' self-assessment and provides unique benefits with respect to the collaborative aspects of learning.

MATERIALS AND METHODS

The VesARlius Anatomy Teaching System

The VesARlius system allows medical students to engage in collaborative, team-based anatomy learning sessions. It is aimed at supplementing traditional education paradigms such as anatomy textbooks, 3D models, and computer-based online platforms with a unique AR learning experience. An overview of the entire user interface can be seen in Figure 1A and in the Supplemental Material video. One of the main functionalities of VesARlius is to provide students with the possibility to explore a virtual 3D model of the human body, which includes many anatomical structures of the thorax, abdomen, and pelvis. In addition to the virtual human body model, section images from computed tomography (CT) can be displayed above the 3D model or directly within it, see Figure 1B. All virtual organ models were obtained from the CT images using a combination of manual and semi-automatic segmentation (Yushkevich et al., 2006) using version 3.8 of the ITK Snap medical image segmentation tool (University of Pennsylvania, Philadelphia, PA). Hence, there is a one-to-one correspondence between the virtual 3D model and the CT images. This allows students to select a specific point in one of the CT images such that the exact same point will be highlighted in the 3D model. Similarly, when selecting a specific point on the 3D model, the



3D Models
☑ Arteries
☑ Skeleton
☑ Lungs
☑ Bladder
☑ Bowel
☑ Colon
☑ Kidneys
☐ Hide All
☑ Veins
☑ Liver
☑ Pancreas
☑ Spleen
☑ Stomach
☑ Trachea
☑ Gallbladder

☐ Laser Pointer
☑ Place Pins
☐ Shared Room
☐ DocCheck
☑ Highlighting
☑ Show Tooltips
☐ Virtual X-Ray

Figure 1.

Overview of the VesARlius system. A, the different components of the VesARlius user interface; B, Computed tomography (CT) section images placed within the virtual 3D model.

corresponding point is displayed in all three CT images (axial, sagittal, and coronal). Both the initial segmentation and a subsequent refinement were performed by two experienced medical students from the Faculty of Medicine, Ludwig-Maximilians University, Munich, Germany.

Besides the 3D models and the section images, the system provides a set of functionalities that are specifically aimed at facilitating the collaboration between students during joint learning sessions. In the following paragraphs, a short description for each of these features is presented.

Synchronized rooms. The main feature to enable collaborative learning in VesARlius are synchronized rooms. For all users inside the same room, the entire state of the application is synchronized in real-time. This applies to all functionalities of the application, such as rotation of the 3D model, selection of individual anatomical structures or image sections, as well as updates to the user interface. At all times, users are free to enter existing rooms, switch between them, or create new ones. Figure 2 depicts a scene in which a group of students collaboratively interact with the VesARlius system.

Individual content placement. The only setting that is excluded from the above room synchronization is the position of the system's virtual content (i.e., the user interface & the 3D model). All users can freely choose to position their individual copy of the application in the environment. While this positional synchronization could easily be achieved using marker-tracking, it severely limits the number of users that can observe a specific virtual object from a given position. Especially when working in teams of co-located users or in restricted environments with limited space, students can thus position their individual copy such that they can comfortably move around it without disturbing other users.

Laser pointer. To direct the focus of users to a specific object of interest, VesARlius integrates a virtual laser pointer. A small red circle is displayed at the location where the gaze direction vector of the currently active presenter intersects with a virtual object. There can be one presenter for each synchronized room and all users can take over the laser pointer to facilitate communication between them.

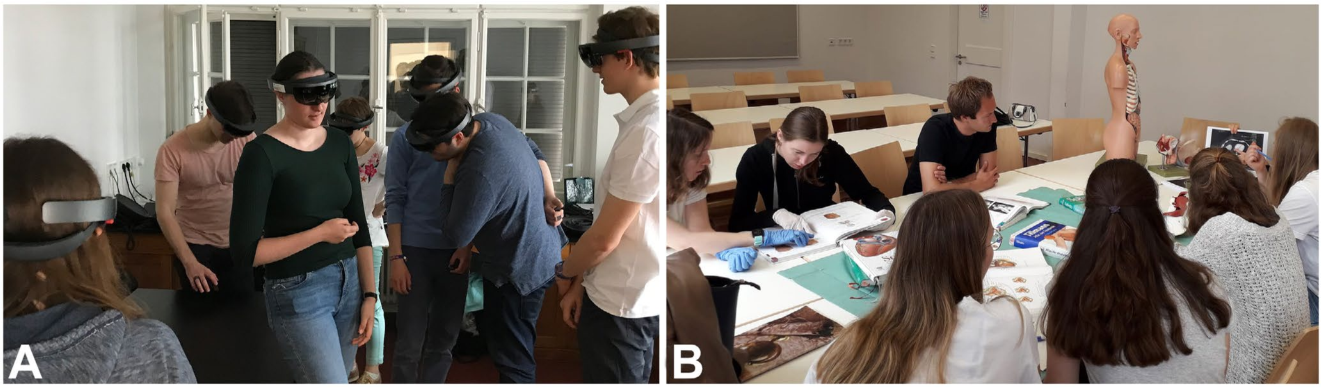


Figure 2.

Study participants during the collaborative group learning session. A, experimental group working with VesARlius; B, control group working with anatomy textbooks and 3D models.

Colored pins. A more permanent focus on structures can be achieved by placing colored pins on the surface of the 3D model. Within a synchronized room, the position of these pins is synchronized and every user has the ability to manipulate the pins. Additionally, a list of all active pins including the name of the associated anatomical structure is part of the VesARlius user interface. Figure 1A shows an example of seven colored pins that have been placed at various different anatomical structures in the 3D model.

Experimental User Study

An experimental user study with first-year medical students was conducted to evaluate the VesARlius AR system with respect to its potential for enabling interactive and collaborative anatomy learning in teams. During a full-day seminar, the learning outcome of a group of students studying topographic anatomy with VesARlius (Figure 2A) was compared to that of another group learning with traditional anatomy textbooks and 3D models (Figure 2B). Figure 3 gives an overview of the individual parts of the experimental user study in chronological order.

Participants. The study was conducted at the Faculty of Medicine at the Ludwig-Maximilians University, Munich, Germany. A total of 16 first-year medical students (11 females, 5 males) with a mean age of 21.0 ± 2.9 years were recruited to participate in the user study. All students had previously finished the course on macroscopic anatomy already, which consisted of both a theoretical part with 90 hours of traditional lectures as well as a practical laboratory part including a mandatory dissection course. While none of the students used a Microsoft HoloLens or any other AR HMD before, some students had prior experience with smartphone-based AR (2.31 ± 1.20) and computer games (3.44 ± 1.90), both reported using a seven-point Likert scale. All students participated voluntarily in the user study and received a total of 80€ as monetary compensation. Additionally, all student data were recorded anonymously during the user study. From each of them, written consent was obtained for the use of data and photos for publication. It was further ensured that no link can be established between the participants and the data collected.

Pretests: anatomy knowledge and mental rotation. After a short opening session introducing all students to the general schedule as well as the goals of the user study, they were asked to take two paper-based pretests without prior notice: (1) an anatomy knowledge test and (2) a mental rotation test.

The anatomy knowledge test took place in a large auditorium with students spatially distributed to avoid copying answers from neighboring students and was co-designed by two anatomists responsible for the anatomy teaching curriculum at the Chair for Vegetative Anatomy, Ludwig-Maximilians University in Munich, Germany. The test consisted of 20 multiple choice questions about topographic anatomy that were all comparable in both style and difficulty to the questions administered during the anatomy part of the first main German medical examination. For all test questions, there were five potential answers to choose from with only one of them being correct. All 100 response options for the 20 questions of the test were categorized based on Bloom et al.'s taxonomy of learning (Bloom et al., 1956). From the six available domains, the test contained only the first two, namely “Knowledge” (71 response options) and “Comprehension” (29 response options). While the former is concerned with remembering previously learned material or retrieving relevant concepts from long-term memory, the “Comprehension” domain involves being aware of the underlying message and constructing meaning from a given piece of information. For each of the 20 test questions, students were given 45 seconds to answer, yielding a duration of 15 minutes for the test preparation time. Figure 4A illustrates an exemplary anatomy question from the test. Considering the fact that the participants had recently completed their anatomical training, it could be assumed that the students have a good basic knowledge of anatomy. In order to obtain an additional learning effect due to the use of the two learning modalities and to avoid systematic bias, the test questions were designed according to the students' level of knowledge. Therefore, the questions were more demanding for the participants compared to questions for beginners.

Following the anatomy knowledge test, students were asked to complete another test assessing their mental rotation ability. During the paper-based test, students were presented with twenty questions, each containing two image pairs of Shepard and Metzler-like block stimuli (Ganis and Kievit, 2015). For each question, one image pair contained two identical block stimuli with one being a rotated version of the other. In the second image pair, the two block stimuli were not identical, but reflected mirror images of the other. Students had 90 seconds to complete the entire test and identify the block stimuli that were identical. According

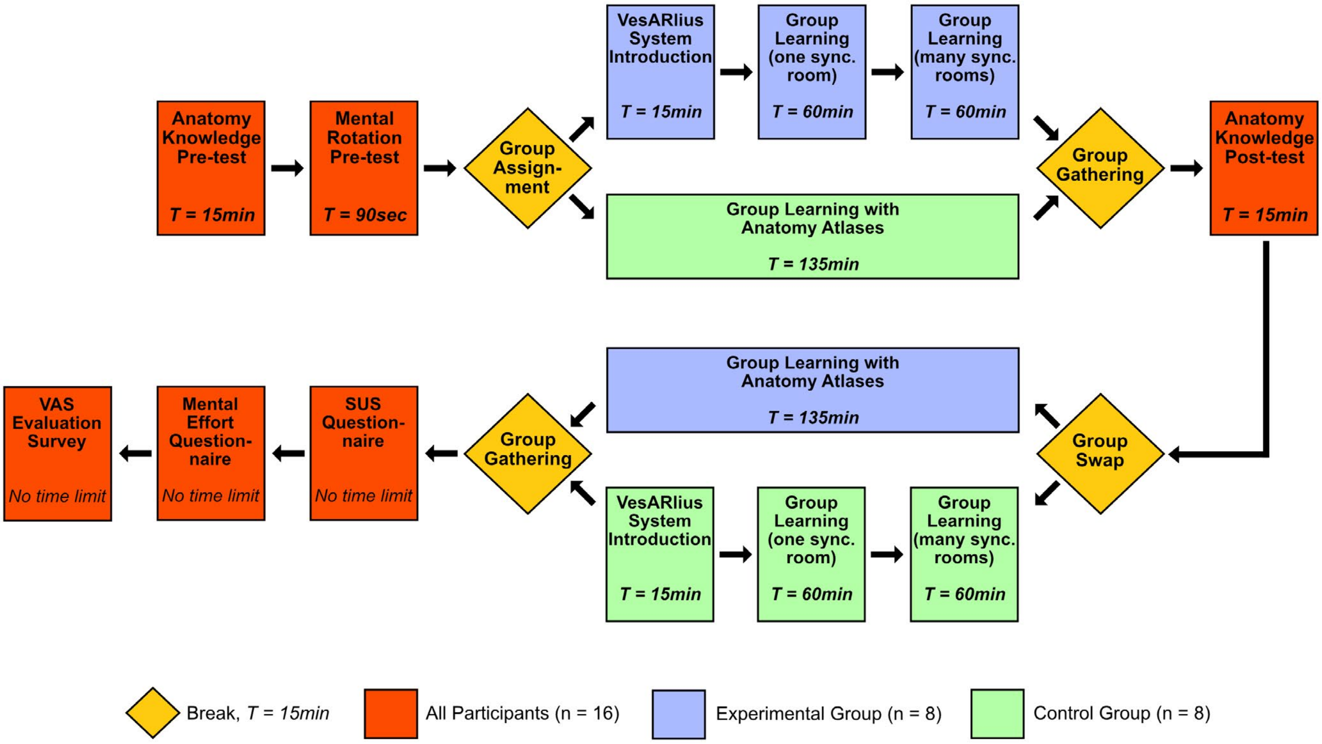


Figure 3.

Chronological overview of the different sections of the experimental user study, including the available time (T) for each section.

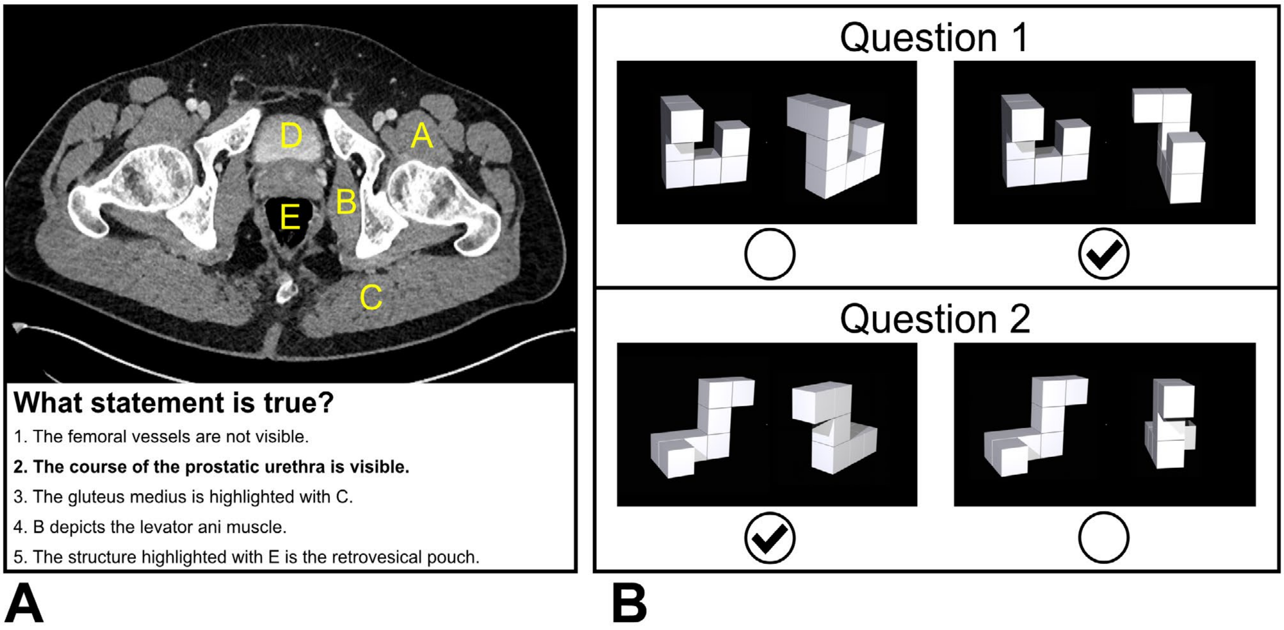
to the original experiment by Ganis and Kievit, response times (RT) and error rate (ER) percentages depend on the rotation amount of the second shape. Furthermore, four different degrees of rotation (0°, 50°, 100°, or 150°) were proposed. The present mental rotation test was designed to be a real challenge for the students as it only contained pairs of images where the second form was rotated by either 100° or 150° (each representing 50% of the test questions). Two example questions are shown in Figure 4B. The primary goal of the mental rotation test was for group assignment, which is discussed in the following paragraph.

Group assignment. After students finished the pretests there was a 15 minutes break during which the group assignment was performed. On the basis of the results obtained during the two pretests, students were manually assigned to either the experimental group (working with VesARlius on the HoloLens) or the control group (working with anatomy textbooks and 3D models). Thus, both groups contained eight students with comparable anatomy knowledge (HoloLens: 25.65 ± 9.80%, Theory: 25.65 ± 6.25%) and mental rotation skills (HoloLens: 41.90 ± 20.35%, Theory: 41.90 ± 27.90%). Students in the experimental group had a mean age of 21.4 ± 3.6 years (5 females, 3 males) compared to 20.6 ± 2.3 years (6 females, 2 males) in the control group.

Collaborative group learning session. The collaborative group learning session represented the main part of the user study. Students in the experimental group worked with the VesARlius application on Microsoft HoloLens HMDs, while three different types of anatomy textbooks (Paulsen and Waschke, 2011; Drake et al., 2014; Tillmann, 2016), two of each type, as well as three 3D organ models of a male torso, a male pelvis, and a female pelvis (SOMSO® MODELLE GmbH, Coburg, Germany) were distributed in the control group. In both groups, the same CT image data were available. Figure 2 shows both groups in their respective learning environments.

At the beginning of the session, the learning objectives were communicated to students in both groups. These were derived from the contents of the pretest and focused on the topography of organs in the abdominal and pelvic region. In particular, students were asked to locate and investigate all organs that were subject to questions in the pretest and study their vascularization. Furthermore, students had to review and learn about the relation of the abdominal and pelvic structures to each other as well as their location (specifically their height) within body. The learning objectives were deliberately set very broadly without stating explicit learning goals such as the identification of specific anatomical structures to avoid knowledge bias in the posttest.

For students in the experimental group, the collaborative learning session was divided into three parts. As none of the students previously used an AR HMD, the first part of the session was a 15-minutes tutorial to get familiar with the general usage of the HoloLens as well as all functionalities specific to the VesARlius application. At the end of the tutorial, all students could see their individual copy of the VesARlius application. During the second part of the learning session (60 minutes), students were asked to work together within one synchronized VesARlius room. This way, the entire state of the application was identical for every student and all previously described collaboration features could be used jointly. In the third and last part of the session (60 minutes), students were free to stay in the same synchronized room, open a new room with other



What statement is true?

1. The femoral vessels are not visible.
2. **The course of the prostatic urethra is visible.**
3. The gluteus medius is highlighted with C.
4. B depicts the levator ani muscle.
5. The structure highlighted with E is the retrovesical pouch.

Figure 4.

Examples of questions. A, question from the anatomy knowledge pretest; B, two questions from the mental rotation pretest.

students, or completely work with the system on their own.

Similarly, students in the control group were provided the same time (135 minutes) to collaboratively focus on the learning objectives using the provided anatomy textbooks and 3D models. The entire collaborative learning session in both groups was self-directed, such that students did not have any additional help in the form of an experienced anatomist or teacher that could answer specific questions.

Anatomy knowledge posttest. After the collaborative group learning session and a short break of 15 minutes, students from both groups gathered in the auditorium to complete another anatomy knowledge assessment test. While the general structure of this test was identical to the one of the pretest—20 questions with 5 response options each and the categorization of questions into image-based and text-based—none of the questions was exactly repeated to avoid memory bias. Similar to the anatomy knowledge pretest, Bloom et al.'s taxonomy of learning was employed for classifying the response options. For the slightly more challenging posttest, only 64 response options came from the "Knowledge" domain while 36 belonged to the "Comprehension" domain. All questions in both the anatomy pre-test and the post-test were rated equally and each gave one point.

Extended group learning session. During the collaborative group learning session, only one half of the students worked with VesARlius. In order to also allow students from the control group to work with the system and to capture their opinion toward it, there was another group learning session during which the groups were flipped. This way, all students worked with both VesARlius and traditional anatomy learning modalities for at least 135 minutes. At the beginning of the extended group learning session, students were asked to focus on the question whether they think they would have performed better with the system they had not worked with during the first learning session and focus on the advantages and disadvantages of both.

Post-experiment survey questionnaires. As the last part of the experimental user study, students were asked to provide their subjective feedback concerning the usability of the VesARlius system as well as the mental effort levels experienced during the user study. Additionally, a survey questionnaire was designed to evaluate the general opinion of students toward the system and its potential for supplementing existing anatomy learning paradigms.

For subjectively assessing the usability of the VesARlius system, an industry-standard System Usability Scale (SUS) questionnaire was used (Brooke, 1996). It presents a convenient method to evaluate the technical aspects of a generic system and consists of a ten-item questionnaire with five possible response options ranging from "Strongly agree" to "Strongly Disagree." The final SUS score resulting from the questionnaire can be seen as a measure of the system's usability and maturity, with a SUS score above 68 considered as above average and SUS scores above 80.3 considered as in the top 10th percentile. In terms of school grades, a score of 68 would correspond to a C, while everything above 80.3 can be considered an A.

Following the SUS questionnaire, students continued with another post-experimental survey aimed at measuring the mental effort levels experienced while working with the VesARlius system. Students reported the subjectively perceived mental effort based on a nine-point scale according to Paas, with values above five corresponding to a high cognitive load (Paas, 1992). A count of one corresponded to a "very, very low mental effort level" experienced during usage of the VesARlius system, while a value of nine was associated with a "very, very high mental effort level."

The third and last posttest was an extensive, paper-based evaluation survey comprising a total of 23 statements concerning various aspects of VesARlius including the students' personal attitude toward the system, its potential within the medical curriculum, as well as advantages and disadvantages compared to

Table 1.

Combined Pre- and Posttest Results from the Experimental User Study

		Pretests		Posttests		
Condition	N	Anatomy Knowledge Mean % (±SD)[a]	Mental Rotation Mean % (±SD)	Anatomy Knowledge Mean % (±SD)	SUS[b] Mean Score (±SD)	Mental Effort[c] Mean Score (±SD)
VesARlius	8	25.65 (± 9.80)	41.90 (± 20.35)	50.65 (± 15.00)	83.63 (± 10.58)	4.63 (± 2.67)
Theory	8	25.65 (± 6.25)	41.90 (± 27.90)	43.75 (± 12.15)	76.38 (± 16.49)	5.63 (± 2.26)
All Participants	16	25.65 (± 7.95)	41.90 (± 23.60)	47.20 (± 13.65)	80.00 (± 13.90)	5.13 (± 2.45)

[a]Standard Deviation;[b]System Usability Scale, maximum points = 100;[c]Maximum points = 9.

other learning modalities. The statements from the survey were designed by the same two senior anatomists that designed the anatomy knowledge tests based on the quality criteria defined by Bühner (Bühner, 2011) and Hollenberg (Hollenberg, 2016). For each of the 23 statements, students had to rate their approval on a visual analogue scale (VAS) from 0 (strongly disagree) to 20 (strongly agree). For each statement, there was a 15 cm line on the survey sheet, subdivided into 20 steps, onto which students had to place a mark which signaled their approval rating to the statement. In addition to these 23 survey statements, there was a short questionnaire with three questions regarding the collaborative aspects of the VesARlius system that was based on a seven-point Likert scale. Lastly, the survey contained a section for providing free text feedback where students could describe both positive and negative aspects of the system as well as provide potential suggestions for improvement.

Statistical analysis. Independent samples T-tests were performed to reveal significant differences in terms of anatomy knowledge test results as well as other posttest results between the experimental group (VesARlius) and control group (Theory). The statistical analyses were all carried out using the SPSS statistical package, version 24.0 (IBM Corp., Armonk, NY), with a level of significance set to $P < 0.05$. In the following results section, all descriptive data are presented in terms of mean and standard deviation. Effect sizes are described using Cohen's d, with values below 0.2 considered as a small effect, values between 0.2 and 0.5 considered as a medium effect, and values above 0.8 as large effects.

Ethical approval. All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and ethical standards. The entire data collected during the course of the experimental user study was evaluated anonymously with the permission of students in the form of written informed consent.

RESULTS

Anatomy Knowledge Pretest vs. Posttest Scores

Overall, students were able to achieve significantly higher scores in the anatomy knowledge posttest compared to the pretest. For all 16 students combined, the percentage of correct answers increased from 25.65 ± 7.95% in the pretest to 47.20 ± 13.65% in the posttest. These differences were significant with a high effect size at the $P < 0.001$ level ($t(30) = -5.46$, $P < 0.001$, Cohen's $d = 1.93$). Looking at both groups individually, significant differences between the two tests could be found. Students in the control group improved from 25.65 ± 6.25% to 43.75 ± 12.15%. Similarly, students in the experimental group improved from 25.65 ± 9.80 to 50.65 ± 15.00%. In both cases, these differences were significant (Theory: $t(14) = -3.75$, $P = 0.002$, Cohen's $d = 1.87$; HoloLens: $t(14) = -3.95$, $P = 0.0015$, Cohen's $d = 1.97$). While average posttest scores were higher in the experimental group compared to the control group, these differences were not significant ($t(14) = -1.01$, $P = 0.33$, ns). Both Table 1 and Figure 5 provide an overview of these results.

Both anatomy knowledge tests were designed for students with a sound understanding of anatomy, therefore, the item difficulty in the pre-test for all participants was quite challenging (Mean ± SEM: 0.25 ± 0.037). The questions of the posttest were no longer that difficult (0.47 ± 0.047; $P = 0.0007$), which showed that a learning effect can be achieved by both groups. For the experimental group (pre-test 0.25 ± 0.043; post-test 0.50 ± 0.052; $P = 0.0007$), the test was even slightly easier than for the control group (pre-test: 0.25 ± 0.044;

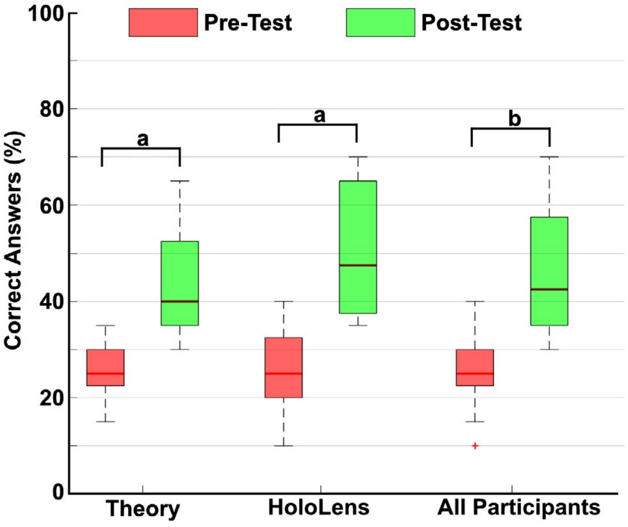


Figure 5.

Percentages of correct answers during both the anatomy knowledge pre and posttest. The results are reported for both the control group (Theory) and experimental group (HoloLens) individually as well as combined. Significant differences are indicated as follows: [a]$P < 0.05$; [b]$P < 0.001$.

post-test: 0.45 ± 0.066; $P = 0.0172$). The discrimination index (pre-test: D = 0.2 ± 0.059; post-test: D = 0.28 ± 0.066) as a basic measurement of the validity of an item showed no significant difference between the two tests. This indicates that the test was fair (index between 0.1 and 0.3). In order to assess the reliability of the test, even within this small group of participants, Guttman's Lambda-6 (G6) was calculated for the post-test. This estimates an acceptable internal reliability with $\lambda = 0.69$.

System Usability Scale

The perceived usability of the VesARlius system was measured using a SUS questionnaire. Overall, students provided a very positive feedback very high SUS scores were recorded for the VesARlius system with an average SUS score of 80.00 ± 13.90 for all students combined. Interestingly, studying the SUS scores for the two groups individually revealed that on average, students in the experimental group rated the system with higher scores than students in the control group. For the former, the average SUS score was 83.63 ± 10.58 compared to 76.38 ± 16.49 in the control group.

However, these differences were not significant ($t(14) = 1.05$, $P = 0.31$, ns). Considering that a SUS value of 80.3 is considered in the upper 10th percentile (corresponding to a school grade A), the usability of VesARlius was rated very positively, though there is still some room for improvement.

Mental Effort

The comparison of mental effort levels experienced during the collaborative group learning session with VesARlius was performed by means of a nine-point scale by Paas (1992). For all students combined, mental effort levels were rather high with 5.13 ± 2.45. Similar to the results of the SUS questionnaire, there were slight variations between the two groups. While these differences were not significant ($t(14) = -0.81$, $P = 0.43$, ns), students in the experimental group provided slightly lower mental effort levels (4.63 ± 2.67) compared to students in the control group that used the VesARlius system after the posttest (5.63 ± 2.26).

Survey

The evaluation survey contained a total of 23 statements (S1 - S23), a short questionnaire on the collaborative aspects of the system, as well as an optional section for free text feedback. The results demonstrate that the VesARlius system was generally perceived as a valuable tool for collaborative anatomy learning and as a great supplement to existing modalities with very specific advantages. The overall results of the main survey, excluding questions on the collaboration aspect and the free text feedback, are listed in Table 2.

Main survey. Students in both the experimental and control group unanimously stressed that sectional anatomy is important for all types of physicians (S1, 18.63 ± 1.26) and that it should be an integral part of the medical curriculum (S2, 18.19 ± 1.60).

In relation to the dissection course, VesARlius was found to offer specific benefits (S5, 5.44 ± 4.32) and all students felt that the system presents a valuable supplement (S4, 16.25 ± 4.54) which should be integrated into the course (S6, 17.94 ± 2.93). However, VesARlius was found to be inappropriate for replacing hands-on cadaveric dissections (S3, 1.56 ± 0.96). When comparing VesARlius to other established anatomy learning modalities (S7–S11), results were mixed. Though students were generally not convinced that anatomy learning solely with VesARlius is sufficient (S12, 15.13 ± 5.78) and that the system to replace traditional anatomy textbooks (S7, 8.38 ± 6.04) or 3D models (S9, 9.00 ± 5.76), they felt that it does offer advantages over the former (S8, 13.38 ± 3.81). Additionally, VesARlius proved to be superior to novel anatomy learning systems such as Anatomage (S11, 17.56 ± 2.85) and the AR Magic Mirror (S10, 17.06 ± 3.86), which all students knew from prior seminars (Bork et al., 2019a). The system was perceived to offer a fun way of collaborative anatomy learning (S14, 14.63 ± 4.47), with slightly higher values for the experimental group. On top of that, working with VesARlius was found to have a positive effect on motivation (S13, 13.19 ± 5.41) and on anatomy learning in general (S15, 12.88 ± 4.73). Both groups were undecided whether VesARlius is suitable as an introductory tool for anatomy learning and felt that a certain level of anatomical expertise should be a prerequisite (S20, 11.63 ± 7.19). In terms of benefits for anatomy knowledge acquisition, students thought that VesARlius can be used effectively for improving their learning success (S17, 17.63 ± 2.83) and for understanding certain anatomical concepts better (S16, 14.81 ± 4.67). Overall, students felt that working with VesARlius during the collaborative group learning session improved their anatomical knowledge (S19, 15.25 ± 4.63). Additionally, all students thought that working with VesARlius improved their three-dimensional understanding of the anatomy (S18, 16.19 ± 4.29). Concerning the maturity of the system (S21–S23) and its potential for self-directed anatomy learning in groups, the majority of students thought that the system is mature and well-thought out, although there is still room for improvements (S21, 12.88 ± 2.33). Most importantly, all students would like to spend more time with VesARlius (S23, 17.69 ± 3.13) and could imagine to regularly work with the system in independent anatomy learning sessions (S22, 19.06 ± 1.80).

Comparing the approval ratings of the students for all 23 statements in both groups, they were slightly higher in almost all cases within the experimental group, though significant differences could be found for only two statements. This was the case for the question of whether learning anatomy with VesARlius alone would be a great challenge, for which students in the control group provided significantly higher scores than students in the experimental group (S12, Control: 18.25 ± 2.43, Experimental: 12.00 ± 6.59, $t(-2.52)$, $P = 0.02$, Cohen's d = 1.26), and for the question of whether VesARlius awakened the students' interest in anatomy, for which the students in the experimental group also gave significantly higher scores (S16, control: 10.64 ± 4.24, experimental: 15.13 ± 4.29, $t(14) = 2.22$, $P = 0.04$, Cohen's d = 1.11).

Questionnaire–collaboration features. The survey contained a separate questionnaire about the collaborative features of VesARlius which form an essential component of the overall system. The following three questions were included: Q1 – I found the collaborative features of VesARlius useful; Q2 – I think the collaborative features of VesARlius were sufficient; Q3 – I found the collaborative features of VesARlius disturbing and would rather learn by myself. Overall, students considered the collaborative features as useful (Q1, 5.63 ± 1.36) and not disturbing the learning session (Q3,

Table 2.

Results from the Main Part of the Post-Experimental Evaluation Survey

	Visual Analogue Scale[a]		
	All Participants	**Theory**	**VesARlius**
Survey Statements	**Mean (± SD)[b]**	**Mean (± SD)[b]**	**Mean (± SD)[b]**
1. Sectional anatomy is of decisive importance for the profession of physicians	18.63 (± 1.26)	18.75 (± 1.04)	18.50 (± 1.51)
2. Sectional anatomy should be an important part of the medical curriculum	18.19 (± 1.60)	18.38 (± 1.51)	18.00 (± 1.77)
3. I can imagine that VesARlius will eventually replace the dissection course	1.56 (± 0.96)	1.50 (± 0.76)	1.63 (± 1.19)
4. VesARlius is a very suitable supplement to the dissection course	16.25 (± 4.54)	16.50 (± 3.25)	16.00 (± 5.78)
5. VesARlius does not add any benefits in comparison to the dissection course	5.44 (± 4.32)	6.13 (± 4.32)	4.75 (± 4.50)
6. VesARlius should be integrated into the dissection course	17.94 (± 2.93)	17.38 (± 3.29)	18.50 (± 2.62)
7. I can imagine that anatomy learning with VesARlius can replace learning with atlases	8.38 (± 6.04)	7.00 (± 6.35)	9.75 (± 5.80)
8. VesARlius has great advantages over a textbook or atlas	13.38 (± 3.81)	11.75 (± 3.45)	15.00 (± 3.63)
9. I can imagine that anatomy learning with VesARlius can replace learning with 3D models	9.00 (± 5.76)	7.00 (± 6.09)	11.00 (± 4.99)
10. Anatomy learning with VesARlius is superior to learning with the Magic Mirror	17.06 (± 3.86)	16.00 (± 4.34)	18.13 (± 3.23)
11. Anatomy learning with VesARlius is superior to learning with the Anatomage table	17.56 (± 2.85)	16.63 (± 3.38)	18.50 (± 2.00)
12. Learning anatomy with VesARlius alone would be a great challenge for me	15.13 (± 5.78)	18.25 (± 2.43)[c]	12.00 (± 6.59)[c]
13. Working with VesARlius increases my motivation to learn anatomy	13.19 (± 5.41)	13.25 (± 3.73)	13.13 (± 6.98)
14. Anatomy learning with VesARlius is fun	14.63 (± 4.47)	13.38 (± 4.00)	15.88 (± 4.82)
15. Working with VesARlius has awakened my interest (even more than before) in anatomy	12.88 (± 4.73)	10.63 (± 4.24)[c]	15.13 (± 4.29)[c]
16. Learning with VesARlius increases my chances of success in understanding anatomy	14.81 (± 4.67)	12.50 (± 5.15)	17.13 (± 2.85)
17. I'm sure that the system can be used to my advantage and to improve my learning success	17.63 (± 2.83)	16.50 (± 3.16)	18.75 (± 2.05)
18. Working with the VesARlius system improves my three-dimensional understanding	16.19 (± 4.29)	16.38 (± 2.72)	16.00 (± 5.66)
19. The exercise was profitable with regard to my anatomical knowledge	15.25 (± 4.63)	15.13 (± 4.73)	15.38 (± 4.87)
20. The VesARlius system is suitable as an introductory tool to anatomy	11.63 (± 7.19)	10.88 (± 7.45)	12.38 (± 7.35)
21. The VesARlius system seems mature and well thought out	12.88 (± 2.33)	13.13 (± 2.17)	12.63 (± 2.62)
22. I can imagine working independently with the VesARlius system	19.06 (± 1.80)	18.75 (± 2.19)	19.38 (± 1.41)
23. I would like to spend more time working with the VesARlius system	17.69 (± 3.13)	16.63 (± 3.93)	18.85 (± 1.75)

Results are listed both for all (n = 16) participants combined as well as individually for the experimental (VesARlius) and control (Theory) group.[a]Visual Analog Scale (0–20), where 0 = completely disagree and 20 = completely agree;[b]Standard Deviation;[c]Significant Difference at $P < 0.05$.

2.00 ± 1.37). They also found the features to be sufficient for enabling collaborative learning in teams of co-located students (Q2, 5.44 ± 1.32). While Likert-scale ratings were slightly better in the experimental group, no statistically significant differences were found.

Free text feedback. At the end of the survey, students had the chance to provide free text feedback on both the VesARlius system and on their experience during the experimental user study. Three predefined free text feedback categories were included in the survey: i) positive aspects and benefits, ii) problems and limitations, and iii) suggestions for improvement. Overall, students greatly appreciated working with the system and their comments were in accordance with the positive results from the main survey.

In terms of positive feedback, all sixteen students provided a written statement with their feedback. More than half of the students (N = 9) mentioned that VesARlius provides a much better 3D visualization of anatomical structures than traditional textbooks, specifically for learning the course of individual vessels (N = 4) and for gaining a better spatial understanding of both topographic anatomy (N = 7) as well as the relation between certain structures (N = 3). In accordance with statements S13 – S14 from the main part of the survey, some students specifically pointed out that VesARlius presents a fun way of learning anatomy (N = 4) which leads to an increased motivation (N = 2). Additionally, five students explicitly valued the collaborative features of VesARlius, which were found to "make the entire learning experience much more fruitful," to "offer a [very effective] means to jointly discuss about the anatomy," and to "provide a great way to share knowledge with other students."

In the second feedback category concerning the problems and limitations of the system, fourteen students provided feedback. Their comments were mainly restricted to technical shortcomings of the hardware (i.e., Microsoft HoloLens) employed during the experimental user study. The overall weight of the HMD was found to be too high (N = 5) which caused pain for a few students while wearing it without a nose piece (N = 4). Additionally, the small field of view was outlined as a system limitation by six students. Confirming the results of statement S3 from the survey, almost half of the students explicitly stressed that VesARlius cannot replace hands-on dissection with body donors (N = 7) as it "misses the tactile feedback" and "does not provide [intuitive] gestures to manipulate and deform virtual 3D organ models." Lastly, two students pointed out in their feedback that small structures such as specific arteries and veins are difficult to select using the existing input methodologies of HoloLens.

The third and last feedback category contained students' comments regarding potential improvement suggestions and was answered by twelve students. A reoccurring theme was to include more content in terms of 3D anatomy models such as muscles, male and female reproductive organs, as well as the heart (N = 8). On top of this, several students expressed the wish to include additional CT and MRI volumes, including clinical cases (N = 3). Another feature request was concerned with the interaction of 3D models. Two students proposed a functionality to "pick and organ and enlarge it to see fine-grained annotations." Lastly, a few students (N = 3) mentioned that a "quiz mode" could be a very valuable addition for "reviewing the acquired anatomical knowledge."

DISCUSSION

The present study compared the effectiveness of the VesARlius system for collaborative AR anatomy learning with traditional learning using textbooks and 3D models. Learning outcome was measured using a pretest-posttest design and significant differences between the test scores could be found for both groups. While posttest scores in the experimental group (VesARlius) were slightly higher than in the control group (Theory), these differences were not statistically significant. In addition to the anatomy knowledge tests, students evaluated the usability and experienced cognitive load while using the VesARlius system by means of a SUS questionnaire and a Paas mental effort test. In terms of usability, the system was generally perceived very well by students with an average SUS score of 80.00 ± 13.90, corresponding to an A- in terms of school grades. The level of mental effort tended toward the upper end of a seven-point Likert scale with an average score of 5.13 ± 2.45. Finally, the subjective attitude toward the VesARlius system, which was measured by a survey, was generally very positive and students could imagine using the system as a complementary tool for anatomy learning. In the following, the most important results of this study are discussed in detail on the basis of the previously formulated hypotheses.

Learning Outcome

With regard to the learning outcome, it was hypothesized that students learning with the VesARlius system have an equivalent or better educational performance compared to traditional anatomy learning with textbooks and 3D models. This hypothesis could be partially verified by the study results, as the posttest scores were higher in the experimental group and the qualitative survey findings suggested distinct advantages over traditional learning paradigms, though none of these differences were statistically significant. The positive results are in line with a series of previously published works that have indicated positive learning effects of AR systems when integrated into the medical curriculum (Chien et al., 2010; Küçük et al., 2016; Bork et al., 2019a). On the contrary, a recent study by Wainman et al. (2019) found that HoloLens-based AR is significantly inferior to studying pelvic anatomy using 3D models. In their study, students had 10 minutes to remember 20 anatomical structures of the pelvis with each modality. Compared to a control group studying with 2D images of key views, the best performance was measured for the 3D model group (70% accuracy increase) while only a non-significant change of 2.5% was found for the AR group. While in the present study, students were given considerably more time to interact with the VesARlius AR system and the study objectives were more complex than simply remembering names of anatomical structures, additional studies are required to better determine the specific benefits of AR for gross anatomy learning, in order to integrate it into the medical curriculum in a way that will allow students to derive the maximum benefit from it. In addition, compared to the AR application used in the study by Wainman et al. (2019), VesARlius contained a much larger number of features, which could be another possible explanation for the contradictory results. AR has unique advantages in educational environments, particularly in terms of student motivation, engagement or interactivity, and should not be reduced to a mere additional means of presenting information (Billinghurst and Duenser, 2012; Diegmann et al., 2015). These advantages are also evident in the positive attitude of the participating students toward VesARlius, both in terms of subjective free text feedback (qualitative) as well as survey results (quantitative). They corroborate the recent call for multi-modal teaching opportunities for actuating the paradigm shift toward self-directed, student-centered, exploratory anatomy learning (Sugand et al., 2010; Cheng and Tsai, 2013; Singh and Kharb, 2013; Diegmann et al., 2015; Estai and Bunt, 2016; Akçayır and Akçayır, 2017; Phillips et al., 2018). The high SUS score that VesARlius received from medical students along with students' subjective preference of VesARlius over comparable systems such as Anatomage (Anatomage Inc., San Jose, CA) and the AR Magic Mirror (Bork et al., 2019a) further demonstrates the potential of the system to fulfill the above criteria and serve as a complementary tool for anatomy education. However, the results of the mental effort questionnaire showed that great care should be taken not to overburden students with too much information, as this has been shown to have a negative impact on motivation and learning outcome (Cheng, 2017).

Interestingly, students in the experimental group generally rated the VesARlius system slightly better in almost all relevant evaluation criteria (higher SUS score, lower mental effort, overall better survey ratings). Carrying out the evaluation after a third anatomy knowledge test following the extended learning session could possibly have led to more balanced results, as the students in the control group could not see the immediate benefit of their learning session with VesARlius in terms of test results. However, such a third knowledge test would have blown up the study protocol even more and might have included a systematic bias due to the lack for concentration after a full day of intense studying. Nevertheless, such investigations could be a topic of future research.

Improved 3D Understanding

The second hypothesis was related to the students' perceived spatial ability and stated that learning with VesARlius improves the 3D understanding of the topographic anatomy according to their self-assessment. Interactive AR systems that are aimed at improving the 3D understanding of students are increasingly requested by medical students and educators alike (Moro et al., 2017; Triepels et al., 2018). Previous studies have shown that there is a bidirectional relationship between spatial ability and anatomical learning: spatial ability is predictive of performance in gross anatomy courses, and participation in gross anatomy courses increases students' spatial ability (Garg et al., 2001; Lufler et al., 2012; Vorstenbosch et al., 2013). The experimental results of this study, in particular statement S18 from the survey (*Working with the VesARlius system improves my 3D understanding*), suggest that students in fact perceive the system to improve their understanding about the spatial relations of anatomical structures, verifying the above hypothesis. While a good 3D understanding was also very helpful for many questions in the anatomy knowledge tests and the better overall results in the posttest could potentially be attributed to an improved 3D understanding, this hypothesis has to be tested in a follow-up study and cannot be substantiated by the results of the present study. Lastly, the very positive results for survey statement S18 could potentially have been influenced by the relatively low spatial ability of the pupils, as revealed by the mental rotation pretest, coupled with the rather low number of participants. For a group of students with rather good spatial skills the results might have been slightly different. Whether learning with the VesARlius AR system improves students' spatial ability, therefore, needs to be evaluated in future work, which could involve continuous mental rotation tests over a longer period of time.

Collaborative Learning

The third and last hypothesis was formulated with respect to the collaboration features of VesARlius and stated that these features provide unique advantages to students in the context of anatomy learning. Team-based, collaborative AR learning constitutes the unique selling point of VesARlius and distinguishes it from other academic or commercial systems. Students expressed very positive opinions toward this aspect of VesARlius by explicitly acknowledging the collaboration features as very useful and sufficient in both the dedicated questionnaire and the free text feedback, as well as by providing very high SUS scores for the overall system. During both the collaborative as well as the extended group learning session, students working with the VesARlius system generally preferred to stay within the same synchronized room and to use all available collaboration features. Only five of the 16 students left the large, synchronized room, with two students creating another shared room for themselves and three students learning individually. In comparison, students working with traditional learning materials (i.e., anatomy textbooks and 3D models) quickly separated into smaller groups of 2–3 people and remained within these groups for the vast majority of the entire session. Overall, these results provide supporting evidence that the VesARlius AR system actively stimulates collaborative anatomy learning. While traditional materials such as textbooks and 3D models are an invaluable medium for anatomy learning and students do not want to miss them from their everyday learning schedule, these modalities do not offer the same benefits in terms of interactive collaboration in larger teams. Previous adoption of collaborative AR systems into other educational environments has found similar benefits in terms of increased motivation, interaction, and learning outcome (Yuen et al., 2011; Phon et al., 2014; Martín-Gutiérrez et al., 2015). Therefore, the integration of collaborative AR systems such as VesARlius into anatomy education presents a very natural evolution for combining the benefits of these two worlds. While collaborative learning is associated with unique educational benefits, which confirms the above hypothesis, there are also challenges that have to be considered when designing such collaborative AR systems. One of the most commonly reported challenges in AR in general and collaborative AR in particular is cognitive overload (Chen, 2008; Dunleavy et al., 2009; Phon et al., 2014). In the present study, cognitive load was explicitly measured with the Paas mental effort test during the post-experimental survey and showed a tendency toward the upper end of the seven-point Likert scale, indicating a rather high mental effort. Therefore, designing an intuitive user interface and appropriate scaffolding mechanisms or instructive guides are essential when developing collaborative AR systems to maximize the learning ability of students while simultaneously minimizing the challenge of cognitive overload. In the case of VesARlius, the positive aspects of the system seem to outweigh the mental effort required to interact with the system, which is reflected in the high overall acceptance rate of the system and the very positive feedback from the survey. However, further studies are needed to confirm this trend and to clearly outline in which scenarios high mental effort occurs. Other remaining challenges include the very high costs of the HoloLens (US$ 3,500 per device) as well as several hardware limitations that were mentioned by students in the free text feedback (among others the limited field of view and the rather bulky form factor). Despite these remaining challenges, the present study results represent an important first step toward a modern, multi-modal gross anatomy course, complemented by interactive, student-centered AR systems, and show that collaborative, AR-based anatomy learning is a very promising field of research that should be further explored in the future. One particular avenue for future research is integrating such collaborative AR systems into a cadaveric dissection course for providing additional information to the students. In such scenarios, HMD-based AR systems such as VesARlius can provide immediate benefits as dissections are generally performed in teams and require multiple students to collaborate in a complex environment.

Limitation of this Study

There are a few limitations to the study that have to be mentioned. Firstly, the number of participants was not specifically large. This was merely due to the previously mentioned high device costs and limited availability of the HoloLens. Obtaining such a large number of devices required complex logistics as the eight HoloLenses came from different university chairs. Furthermore, the overall time students worked with VesARlius (two hours), though much longer than a comparable study by Wainman et al. (2019), was still very short with respect to their overall study hours during the preclinical anatomy course. However, such pilot studies with limited interaction times still have the potential to reveal very important insights into the future development of such systems as well as to establish potential integration strategies into the medical curriculum. Nevertheless, future studies with a larger number of participants and extended working hours with the system are required to verify the findings and to establish such novel technologies as valuable, supplementary learning modalities. In terms of 3D understanding and spatial ability, the study design did not include a mental rotation post-test, which might have shown improved results due to working with VesARlius. Since such a test was not performed, it cannot be determined with certainty that 3D understanding has really improved quantitatively, but only qualitatively according to their subjective self-assessment. Finally, another limitation concerns the process of collaborative group learning in the control group. While in the experimental group the learning session consisted of an introduction to the VesARlius system and two parts in which the collaborative functions of VesARlius could be used, students in the control group could decide during the entire time of the group learning session in which way the individual subgroups were formed. By providing the students with a total of six textbooks and three anatomical models, smaller study groups were indirectly stipulated. The fact that the students naturally distributed themselves among these smaller groups shows that the traditional text book as a medium for anatomy learning is inherently limited to very few students working collaboratively, though it would have been interesting to see whether first learning in one large group would have resulted in different perceptions of group learning in VesARlius.

CONCLUSIONS

In this article, the effectiveness and potential of VesARlius, a novel AR system for enabling collaborative anatomy and radiology learning in teams, was investigated. During an experimental user study with 16 first-year medical students, the system was found to significantly increase students' anatomy knowledge, even more than within a control group working with traditional learning modalities such as anatomy textbooks and 3D models. Additionally, students highlighted a number of other benefits of VesARlius such as its potential for increasing the 3D understanding of topographic anatomy, its increased student engagement as well as the positive impact on fun and motivation. The results of this work provide supporting evidence that AR-based learning in teams has the potential to become an important, supplementary element in modern, multi-modal gross anatomy courses that follow the recent paradigm shift toward more active, student-centered and exploratory learning.

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