A Natural Interaction Paradigm to Facilitate Cardiac Anatomy Education using Augmented Reality and a Surgical Metaphor

Dmitry Resnyansky[1][a], Nurullah Okumus[2][b], Mark Billinghurst[1][c], Emin Ibili[3][d], Tolga Ertekin[4][e], Düriye Öztürk[5][f] and Taha Erdogan[5][g]

[1]*School of Information Technology and Mathematical Sciences, University of South Australia, Mawson Lakes, Australia*
[2]*Department of Child Health and Diseases, Afyonkarahisar Health Sciences University, Afyonkarahisar, Turkey*
[3]*Department of Healthcare Management, Afyonkarahisar Health Sciences University, Afyonkarahisar, Turkey*
[4]*Department of Anatomy, Afyonkarahisar Health Sciences University, Afyonkarahisar, Turkey*
[5]*Department of Radiation Oncology, Afyonkarahisar Health Sciences University, Afyonkarahisar, Turkey*

Keywords: Augmented Reality, Visualisation, Cardiac Anatomy Learning, Interactivity, HMD.

Abstract: This paper presents a design approach to creating a learning experience for cardiac anatomy by providing an interactive visualisation environment that uses Head Mounted Display (HMD)-based Augmented Reality (AR). Computed tomography imaging techniques were used to obtain accurate model geometry that was optimised in a 3D modelling software package, followed by photo-realistic texture mapping using 3D painting software. This method simplifies the process of modelling complex, organic geometry. Animation, rendering techniques, and AR capability were added using the Unity game engine. The system's design and development maximises immersion, supports natural gesture interaction within a real-world learning setting, and represents complex learning content. Hand input was used with a surgical-dissection metaphor to show cross-section rendering in AR in an intuitive manner. Lessons learned from the modelling process are discussed as well as directions for future research.

1 INTRODUCTION

Understanding the anatomical composition of the heart is a difficult task for medical students due to the organ's complex arrangement of individual elements and multi-chambered structures (Maresky et al., 2019). Traditional anatomy learning methods are based on 2D images, slides, and plastic models, and can be less effective due to lack of interactivity, and difficulties with understanding 3D structure from 2D materials (Kurniawan et al., 2018; Rosni et al. 2020). Augmented Reality (AR) and Virtual Reality (VR) can enhance anatomy learning by addressing these problems and creating a more interesting, active and flexible learning experience (Bork et al., 2019).

This paper is part of a wider educational project that aims to support effective knowledge transfer of cardiac anatomy and physiology for medical students through innovative technologies. A Head-Mounted Display (HMD)-based interactive Augmented Reality Learning Environment (ARLE) prototype is currently being developed with the aim of communicating the multitude of the heart's inner and outer structure, as well as basic aspects of its circulatory system. This has been designed with the focus of creating a realistic interactive augmented reference medium for

[a] https://orcid.org/0000-0003-3897-7864
[b] https://orcid.org/0000-0001-6082-0818
[c] https://orcid.org/0000-0003-4172-6759
[d] https://orcid.org/0000-0002-6186-3710
[e] https://orcid.org/0000-0003-1756-4366
[f] https://orcid.org/0000-0002-3265-2797
[g] https://orcid.org/0000-0002-3559-8933

Resnyansky, D., Okumus, N., Billinghurst, M., Ibili, E., Ertekin, T., Öztürk, D. and Erdogan, T.
A Natural Interaction Paradigm to Facilitate Cardiac Anatomy Education using Augmented Reality and a Surgical Metaphor.
DOI: 10.5220/0010835400003124
In *Proceedings of the 17th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2022) - Volume 1: GRAPP*, pages 204-211
ISBN: 978-989-758-555-5; ISSN: 2184-4321

students to compare to textbooks, physical models, dissections, and surgical observation sessions.

The intended design goals of the prototype ARLE are: (1) improving the production pipeline of complex, organic models with Computed Tomography- (CT) extracted 3D scan data; (2) increasing learner immersion when interacting with visualisations by facilitating user stereopsis with the aid of a HMD; (3) supporting natural interaction with AR visualisations without the need for marker-based tracking, mobile devices, or physical peripherals; and (4) representing information in a realistic and engaging manner with the aid of graphic and animated content.

This paper focuses on the design of the prototype system and highlights the importance of adopting a multi-layered approach to the creation of visual learning content, and to supporting natural interaction (Piumsomboon et al., 2014). This work deals with a limited subset of the content necessary for the teaching of the anatomical structure of the human heart: in this case, the primary heart aorta, aortic valve, and aortic circulation system.

The rest of the paper is organised as follows:

In section 2, the relevant literature is outlined. Section 3 describes our prototype system and its associated interaction metaphors and a brief rationale for the design decisions made. Section 4 describes an approach to development of visualisations deriving from medical imaging data obtained from CT scans, including 3D asset creation and preparation inside a game engine for adding functionality. Finally, section 5 concludes the paper by reiterating the aim, formulating insights gained, and future work.

2 RELATED WORK

The main advantages of using AR or VR in anatomy learning is that these technologies can help students with lower visual-spatial abilities (Bogomolova et al., 2021) and enable more active, exploratory, and embodied learning, which improves learning efficiency and memory retention (Cakmak et al., 2020).

There is significant research on virtual learning for anatomy students using different delivery modalities, such as highly immersive (stereoscopic; 3D VR) vs. less immersive (desktop). For instance, Kurul et al. (2020) suggest that a 3D immersive VR system can provide a useful alternative to conventional anatomy training methods. In Wainman et al. (2020), VR and AR representations of pelvic anatomy were tested in comparison to photographs and physical models. They found that VR and AR had fewer advantages for learning than physical models, and that “true stereopsis is critical in learning anatomy” (p. 401). In a pilot study (Birbara et al., 2020), a skull anatomy virtual learning resource was developed using Unity, and was made available in different delivery modalities (more immersive and less immersive). The stereoscopic delivery was found to be more mentally demanding and a greater degree of physical discomfort and disorientation was reported by some participants. Moro et al. (2021) compared the effectiveness of delivering human physiology content in AR through the HoloLens HMD and in non-AR on a tablet. The study did not find any significant differences in test scores, and provided evidence that both modes could be effective for learning, although dizziness when using the HoloLens was reported by some participants.

However, other studies suggest that anatomical learning could benefit from the various affordances of AR/VR such as immersive interactivity and visualisation (Samosky et al., 2012; Venkatesan et al., 2021). For example, Gloy et al. (2021) provide an example of this in their development of an immersive anatomy atlas that enables virtual dissection as a way to interact with human anatomical structures. The application (using a HMD and bi-manual controllers) allows users to explore anatomy by modifying organ transparency, toggling overall visibility within a specific radius with an interactive manipulation tool, or revealing and concealing selected geometry by offering a cross-section capability. Higher retention rate was demonstrated by students using the interactive atlas compared to those using traditional anatomical textbooks. Bakar et al. (2021) describe GAAR (Gross Anatomy Augmented Reality) – a mobile AR learning tool. By interacting with 3D objects, video, and information while using the tool, users can experience the perception of operating on a “real” organ (p. 162).

In a review of mobile AR applications for learning biology and anatomy (Kalana et al., 2020), four interactive AR tools have been reviewed: APPLearn (Ba et al., 2019), to support learning biology in secondary schools; a Magic Book application for medical students to learn neuroanatomy (Küçük et al., 2016); an application that combines 3D modelling and AR for learning molecular biology (Safadel & White, 2018); and Human Anatomy in Mobile-Augmented Reality (HuMAR) (Jamali et al., 2015) which focuses on 3D visualisation of selected bones. Kalana et al. (2020) emphasise AR’s potential for visualisation of complex information and enabling active learning. They also review commercial AR applications for learning anatomy, highlighting features that enable interaction between the user and the 3D models, such as using the “Pinch In-Pinch Out” gesture, and controllers for moving 3D models in four directions, rotating and scaling, or “peeling off” the layers of an organ (pp. 582-583).

Romli and Wazir (2021) assess and compare six applications: Web based AR for Human Body Anatomy Learning (Layona et al., 2018); Human Anatomy Learning Systems Using AR on Mobile Application (Kurniawan et al., 2018); AR for the Study of Human Heart Anatomy (Kiourexidou et al., 2015); an AR application for smartphones and tablets for cardiac physiology learning (Gonzalez et al., 2020); a human heart teaching tool (Nuanmeesri, 2018); and a mobile AR application for teaching heart anatomy (Celik et al., 2020). Romli and Wazir (2021) maintain that marker-based, mobile AR systems enable users to scan physical images in the real world, and display 3D visualisations that may be acted upon with the mobile device.

To summarise, a major advantage of immersive HMD-based technologies such as AR/VR to deliver anatomy-related learning content is that it enables unique interaction modalities innate to the hardware. Natural interaction is afforded more readily in the form of simulated dissection and transparency techniques. However, less immersive approaches (specifically, mobile AR with touch-based GUIs) that afford less natural interaction relative to a HMD tend to be more widely used for teaching anatomy. One of the problems that need to be addressed is creation of the anatomy and the visualisation of cardiac blood circulation. For developers, simulation of dynamic fluids for representing physiological processes involving human circulation is one specific challenge (Rosni et al., 2020). Such dynamic visualisation requires the physics processing capabilities of a game engine in order to avoid expensive processing of pre-cached particle animations. The difficulty is compounded by the subsequent limitations of common game engines in rendering liquids in real time at an adequate level of realism.

3 SYSTEM DESCRIPTION

The prototype ARLE affords interaction in three dimensions for engaging with 3D visualisations. Compared to a 2D interaction approach, which uses contact-based touch and swipe gestures to interact with virtual objects, 3D interaction offers a method of natural interaction using depth-tracking hand gestures in 3D space (Mandalika et al., 2017).

The main features of the ARLE are: (1) markerless AR interaction supported by a HMD to provide six degrees of freedom (6DOF) of movement and vision for users in and around the anatomical visualisation; (2) hand-based manipulation of 3D anatomy models, allowing rotation and scaling of the cardiac system; (3) hand-based interaction that uses a cross-section tool in 3D space to dissect anatomy.

A HMD can readily provide stereopsis capability to users, enabling immersive and engaging representations of visual information by displaying anatomy models in actual 3D space. In addition, the depth perception affordances of the HoloLens2 encourage natural interaction using the hands as well the entire body by facilitating a “walkthrough” experience where the user can walk around the AR view (Billinghurst & Henrysson, 2009). This allows learners the freedom to study the organic structure of complex organs through a “hands-on, feet-first” approach by exploring a heart model in physical space with their own hands as well as on foot.

The prototype ARLE uses interactive scale manipulation to represent visual information in a broader context. This contrasts with mobile AR techniques where zoom controls (e.g. sliders, finger swiping) or (physical) device proximity allows users to observe detailed information for a specific object, but seeing “the bigger picture” becomes a challenge. Restricted magnification of an individual object is thus prioritised over the ability to view and understand its global relationship to its neighbours. Object rotation can be achieved through a similar 3D interaction approach. Users can expand and contract the virtual representation by manipulating anchor points on a bounding box that surrounds the heart model. A surgical dissection tool metaphor is included in the natural interaction paradigm by enabling the user to “dissect” models in 3D space by way of a hand-manipulated virtual tool.

4 DESIGN: APPROACH AND OBSERVATIONS

4.1 Equipment and Interaction

The application uses a Microsoft HoloLens2 see-through AR HMD that provides stereo viewing of virtual content, inside-out head tracking, and support for natural two-handed gesture input. The HMD enables viewing of virtual anatomy on top of the user’s physical environment. A 3D model of the primary heart aorta is chosen as the basis of the visualisation, along with an aortic valve animation and animated blood flow simulation. The AR component may be interacted with by gesture-based input, thereby supporting exploration of the anatomical model through scale and rotation controls. Fig. 1 indicates the user-manipulated AR articulated hand controller, and the gesture-based cross-section tool that shows the inner structure of the aorta.

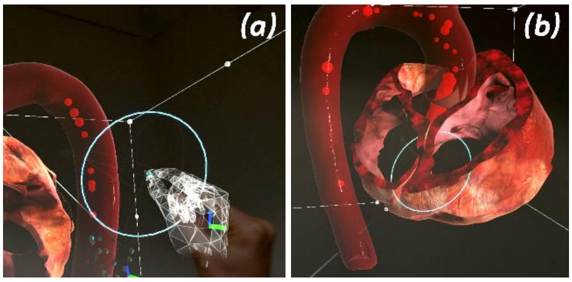

Figure 1: Articulated hand controller operated by user's hand input for operating the cross-sectioning tool (a) and cross-section tool in a passive state of dissection over the left and right atriums (b).

4.2 Production Process

The amended development process of the prototype ARLE comprises the following stages:

1. Scanning: image extraction; image layer splicing; creation of 3D point cloud data sets; and conversion of scan data to 3D geometry.

2. Modelling: conversion of individual polygon arrays to a unified 3D mesh inside a 3D modelling package; cleaning stray polygons and vertices resulting from data point scatter; mesh repair of missing faces and topology; model optimisation and export to game engine; additional modelling and export of aortic valve anatomy to game engine.

3. Texturing: creation of reference textures in a 2D image editor; painting of texture maps for each organ model in 3D painting software; export of maps as Unity-compatible textures.

4. Animation: animation of aortic valve in a 3D modelling package; path construction and particle simulation in a game engine for aorta blood flow visualisation.

5. Rendering: setup of composite materials using painted textures and cross-section shader.

6. Interaction: reconstruction of heart structure using imported anatomical models; addition of hand-based scale/angle manipulation; creation of dissection tool with hand interaction.

4.2.1 Modeling, Animation & Particle Simulation

Information about the patient's anatomy can be transferred to digital media with medical imaging techniques. The most used imaging methods today are Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) (Eichinger et al., 2010). CT is a radiological method that creates a cross-sectional image of the examined area of the body with X-rays (Fig. 2(a)).

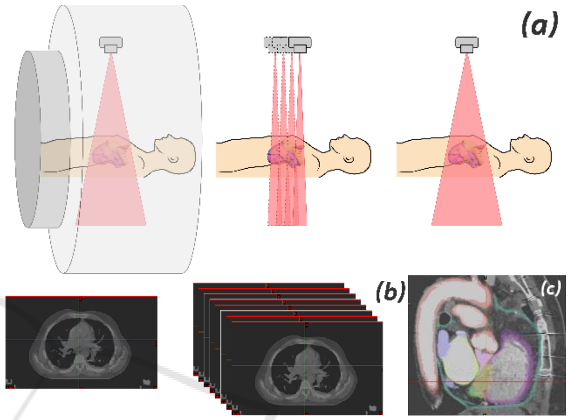

Figure 2: Obtaining a cross-sectional image from CT scan data in MIMICS.

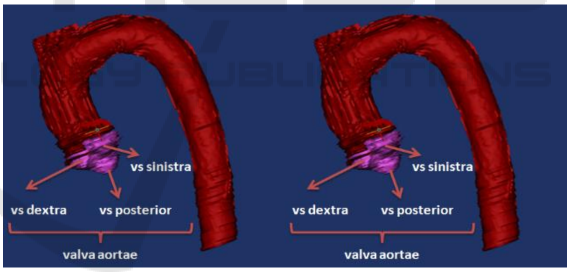

Figure 3: Anatomical structures resulting from 3D scan belonging to the aorta anatomy.

After taking cross-sectional images (Fig. 2(a, b)), the contouring of all anatomical structures of the aorta was started on transverse sections (Fig. 2(c)). These cross-sectional images were modelled by the MIMICS image processing software for 3D design and modelling (Fig. 3). Modelling is the conversion of anatomy structures into three-dimensional form using CT scan data. This procedure requires serious anatomical knowledge, because the image obtained from the anatomy can become quite complex due to the low resolution and patient variations. The geometric mesh surfaces of the primary heart aorta and additional structures were built by converting medical scan data from a CT image to AutoCAD

DXF format for import into a 3D modelling and animation package.

AutoDesk 3DStudio Max was used to edit individual imported DXF polygon object arrays and carry out a conversion, retopology, and mesh repair process for each organ structure. Models were then imported into Unity, where four splines were constructed and positioned inside the aorta to serve as paths for the blood flow simulation. This method allowed for additional control over the paths of each particle simulation by parenting each particle array to the splines (Fig. 4).

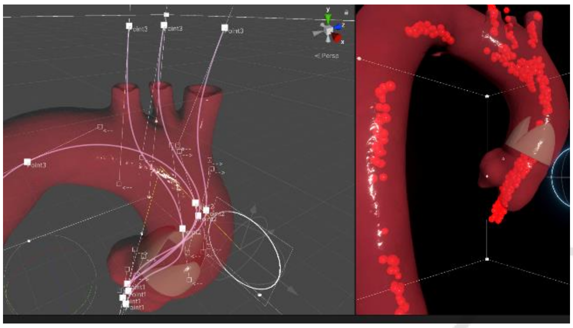

Figure 4: Reconstructed particle animation in Unity's physics engine with newly-constructed splines for directing blood flows.

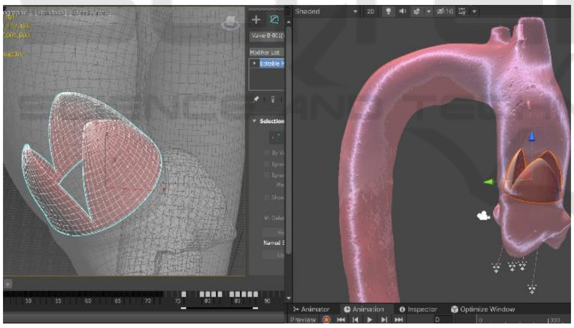

Figure 5: Animation process of aortic valve using Object-Space Modifers in 3DS Max and final looped animation sequence in Unity.

A newly created aortic valve was modelled and animated in 3DS Max (Fig. 5). A cloth modifier was used in the valve model to allow for faster simulation of symmetrical geometry. This provides the ability to animate without a bone-skin-Inverse Kinematics (IK) system. However, export issues arose when converting the valve animation to Unity-compatible formats, none of which presently support Object-Space Modifiers.

Various approaches involving vertex animation-baking yielded a solution in the form of a third-party mesh baker plug-in that was able to pre-cache the animation as an OBJ mesh sequence. When combined with an additional third-party plug-in to import the baked data into Unity, this was able to output the cloth simulation correctly. The animation process was finalised by looping the sequence in Unity's Mecanim, then parenting the new valve to the aorta model, thus allowing for the valve to transition in together with the aorta and blood flow particle animations. Unity's particle physics engine was used to provide a more accurate representation of blood flow by using particle collision in conjunction with a pre-cached valve animation converted to a rigid body (Fig. 6).

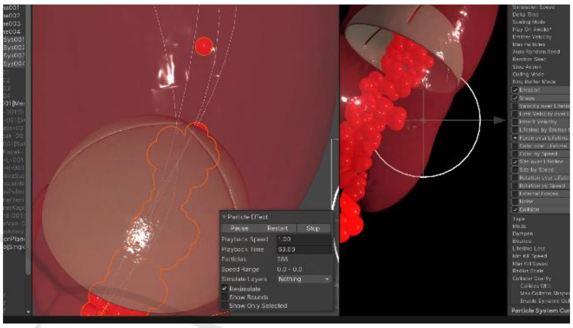

Figure 6: Unity's physics engine was used to provide accurate particle simulation for blood flow animation.

4.2.2 Texturing Mapping and Render Process

The challenges presented by manually unwrapping, stitching and painting textures on complex geometry were overcome with the aid of the Substance Painter software package. This enabled instantaneous, automated UV unwrapping of geometry that included automatic stitching of individual UV maps into a single pelt map. The process was further simplified due to using the same virtual map in 3D space for direct-to-surface painting.

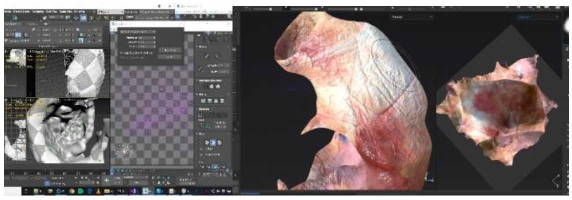

Figure 7: Early UV mapping process in 3DS Max, compared to texture map creation in Substance Painter.

This was achieved by baking the mesh geometry into textures, which allowed for automatic alignment of painted sections and a fully-rendered output of the final texture at all times. This approach was used to dynamically paint and edit custom texture channels on top of a 3D object, then export them as 2D maps, reversing the traditional workflow of 2D to 3D to 2D software package (Fig. 7).

Most traditional workflows do not afford dynamic evaluation of the final result during map editing, and instead rely on the user's imagination, high-end, expensive 2D graphics packages, and third-party tools to produce texture channels. A variety of customised brushes and textures were created by referencing open-source anatomical material in the form of photographs and realistic CGI renders.

Figure 8: Texture maps created in Substance Painter as viewed on HoloLens2 in physical environment.

Once texture sets for each organ structure were imported into Unity, a collection of third-party cross-section shaders with specular shading and normals-rendering support were configured to render the organic material properties of the structures (Fig. 8).

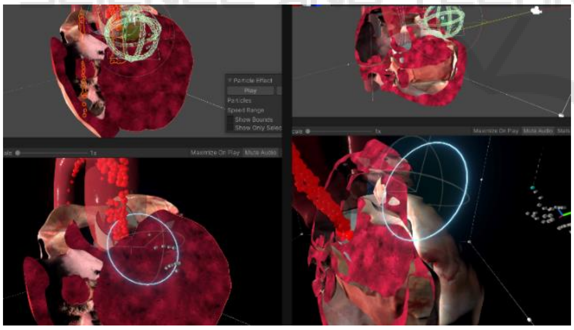

Figure 9: Planar cross-section gizmo configured with compatible shaders and Substance Painter textures applied to anatomy in Unity.

Finally, the cross-section manipulation tool was created in Unity using third-party cross-section shaders and a planar gizmo to adhere to a natural surgical-dissection metaphor inside the AR environment. A simple visual cue was used to denote the tool's position and facing direction to aid usability. Gesture input capability was configured within the tool to allow users to have dynamic control over the dissection process (Fig. 9).

4.3 Observations on Technical Practice and Workflow

One of the first challenges was accurate conversion of CT imaging data into three-dimensional data for the visualisation assets. In order to accurately model the heart aorta, chambers, and its associated anatomical structures, it was necessary to extract image slices from CT data, followed by preparation through combining slices into a 3D AutoCAD object suitable for modelling software. The scatter of physical data points resulting from the scanning process created a challenge during the modelling stage, and required flexible methods for optimising model geometry for texturing and animation.

Artefacts from the initial scan data shifted the workload to optimisation of the complex organic objects in a modelling software package. Since accurate conversion of individual polygons into unified model follows "garbage in, garbage out," it requires initial CT scan data capture with high enough precision to capture the maximum amount of physical geometry of fine and complex organ structures and avoid missing geometry during the conversion (Fig. 10).

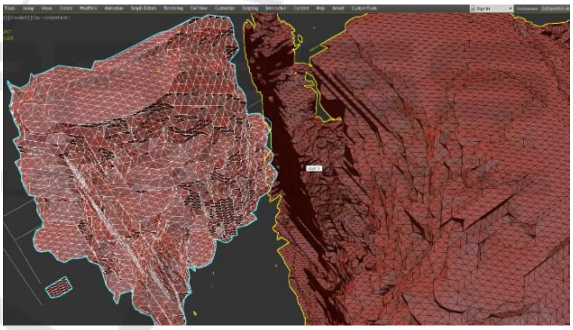

Figure 10: 3D point cloud data during polygon unification process, depicting multiple stray artefacts and missing geometry.

Relatively simple and optimised geometry still required lengthy editing of UV coordinate maps for texturing complex organic structures. This was done using the Adobe Substance Painter 3D painting application that allowed for procedurally generated texturing and auto UV mapping and dramatically decreased the time and effort expended on creation of realistic anatomy assets.

Contrary to traditional methods of using a 3D modelling and animation package to export visualisations, the full range of rendering techniques provided by Unity affords richer experiences that support active learning and the AR medium by using shaders to reveal and conceal interior contents of anatomical structures.

Particle simulation for visualising dynamic processes such as blood flow in an aorta should follow a workflow that prioritises the game engine used for building the ARLE and not 3D animation software. Despite the capability of 3DS Max to produce realistic liquids and synchronise blood pump sequences easily to other animated organs, export compatibility issues and severe memory loads both for exported particle animation caches and Unity's rendering engine make cross-package workflows a challenge. Game engines offer faster computation and rendering of particles, as well as versatility in controlling animation. Physics-based animation is achieved easily, with minimum memory overhead, allowing particles to correspond accurately to imported model geometry and animation.

5 CONCLUSION AND FUTURE WORK

This paper has outlined techniques for creating a photo-realistic cardiac anatomy and physiology visualisation in an AR HMD. This approach enables the learner to observe anatomical content in a real-world setting, while avoiding hands-on interaction with the environment.

The development of the prototype ARLE contributes to AR design practice, particularly to design and development pipelines that focus on HMD-supported AR visualisation. A range of technical challenges related to data visualisation, 3D asset creation, and AR environment design were identified and addressed. These serve as the impetus for some general conclusions: (1) an AR environment that uses HMDs for presenting anatomical visualisations can support immersion and improved usability due to presenting models in three dimensions; (2) anatomical visualisations, particularly those involving compound organ structures of complex shapes and configurations, viewed in an AR HMD may benefit from a dissection metaphor; (3) a walkthrough modality for viewing anatomy visualisations could further shift cognitive load away from manual manipulation actions through hand interaction by allowing users to physically travel around the heart model and interactively study its structure.

These conclusions suggest grounds for evaluation using metrics such as users' dissection frequency and position during interaction, or frequency of physical traversal within the AR space.

Future plans to develop the system include a more precise extraction of CT scans. This should address the problem of missing geometry in complex and thin sections of organic structures, caused by limited scanning resolution. Once obtained, subsequent remodelling and retexturing of structures will take place, creating a more expansive AR representation of the entire heart anatomy. Similarly, the final version of the ARLE will include improvements to animated physiological processes so that the heart circulation may be represented with greater accuracy and realism.

Finally, an evaluation will be conducted of the educational impact of the prototype ARLE on cardiac anatomy knowledge acquisition and learning experience. Once development and a study design are complete, the project will progress to empirical user studies involving selected medical student cohorts in order to observe interaction behaviour and learning efficacy while using the ARLE. There are also plans to develop AI-based evaluation methods. This includes plans to model the patient-specific heart structure with AI algorithms using CT images, to detect possible diseases using the patients' Electrocardiogram (ECG) data, and to animate both the heartbeat rhythm and diseases on the 3D model to support decision making and educational purposes.

ACKNOWLEDGEMENTS

This project was supported by grant from the Afyonkarahisar Health Sciences University Scientific Research Projects Coordinatorship (Project No: 19. TEMATIK.001).

REFERENCES

Ba, R. K. T. A., Cai, Y., and Guan, Y. (2018, December). Augmented reality simulation of cardiac circulation using APPLearn (heart). In *2018 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, pp. 241-243.

Bakar, W. A. W. A., Solehan, M. A., Man, M., and Sabri, I. A. A. (2021). GAAR: Gross Anatomy using Augmented Reality Mobile Application. *International Journal of Advanced Computer Science and Applications*, 12(5), 162-168.

Billinghurst, M. & Henrysson, A., 2009. Mobile architectural augmented reality. In X. Wang & M. A. Schanbel (Eds.), *Mixed reality in architecture, design and construction* (pp. 93-104). Springer.

Birbara, N. S., Sammut, C., and Pather, N. (2020). Virtual reality in anatomy: a pilot study evaluating different delivery modalities. *Anatomical Sciences Education*, 13(4), 445-457.

Bogomolova, K., Hierck, B. P., Looijen, A. E., Pilon, J. N., Putter, H., Wainman, B., and van der Hage, J. A. (2021). Stereoscopic three‐dimensional visualisation technology in anatomy learning: A meta‐analysis. *Medical Education*, 55(3), 317-327.

Bork, F., Stratmann, L., Enssle, S., Eck, U., Navab, N., Waschke, J., and Kugelmann, D. (2019). The benefits of an augmented reality magic mirror system for integrated radiology teaching in gross anatomy. *Anatomical Sciences Education*, 12(6), 585-598.

Cakmak, Y. O., Daniel, B. K., Hammer, N., Yilmaz, O., Irmak, E. C., & Khwaounjoo, P. (2020). The human muscular arm avatar as an interactive visualization tool in learning anatomy: Medical students' perspectives. *IEEE Transactions on Learning Technologies*, *13*(3), 593-603.

Celik, C., Guven, G., and Cakir, N. K. (2020). Integration of mobile augmented reality (MAR) applications into biology laboratory: Anatomic structure of the heart. *Research in Learning Technology*, 28.

Eichinger, M., Heussel, C. P., Kauczor, H. U., Tiddens, H., and Puderbach, M. (2010). Computed tomography and magnetic resonance imaging in cystic fibrosis lung disease. *Journal of Magnetic Resonance Imaging*, 32(6), 1370-1378.

Gloy, K., Weyhe, P., Nerenz, E., Kaluschke, M., Uslar, V., Zachmann, G., and Weyhe, D. (2021). Immersive Anatomy Atlas: Learning Factual Medical Knowledge in a Virtual Reality Environment. *Anatomical Sciences Education*.

Gonzalez, A. A., Lizana, P. A., Pino, S., Miller, B. G., and Merino, C. (2020). Augmented reality-based learning for the comprehension of cardiac physiology in undergraduate biomedical students. *Advances in Physiology Education*, 44(3), 314-322.

Jamali, S. S., Shiratuddin, M. F., Wong, K. W., and Oskam, C. L. (2015). Utilising mobile-augmented reality for learning human anatomy. *Procedia - Social and Behavioral Sciences*, 197 (February), 659–668.

Kalana, M. H. A., Junaini, S. N., and Fauzi, A. H. (2020). Mobile augmented reality for biology learning: Review and design recommendations. *Journal of Critical Reviews*, 7(12), 579-585.

Kiourexidou, M., Natsis, K., Bamidis, P., Antonopoulos, N., Papathanasiou, E., Sgantzos, M., and Veglis, A. (2015). Augmented reality for the study of human heart anatomy. *International Journal of Electronics Communication and Computer Engineering*, 6(6), 658-663.

Küçük, S., Kapakin, S., and Göktaş, Y. (2016). Learning anatomy via mobile augmented reality: Effects on achievement and cognitive load. *Anatomical Sciences Education*, 9(5), 411–421.

Kurniawan, M. H., Suharjito, D., & Witjaksono, G. (2018). Human anatomy learning systems using augmented reality on mobile application. *Procedia Computer Science*, *135*, 80-88.

Kurul, R., Ögün, M. N., Neriman Narin, A., Avci, Ş., and Yazgan, B. (2020). An alternative method for anatomy training: Immersive virtual reality. *Anatomical Sciences Education*, 13(5), 648-656.

Layona, R., Yulianto, B., and Tunardi, Y. (2018). Web based augmented reality for human body anatomy learning. *Procedia Computer Science*, 135, 457-464.

Mandalika, V. B. H., Chernoglazov, A. I., Billinghurst, M., Bartneck, C., Hurrell, M. A., Ruiter, N. de, Butler, A. P. H., and Butler, P. H. (2017). A hybrid 2D/3D user interface for radiological diagnosis. *Journal of Digital Imaging*, 31(1), 56–73.

Maresky, H. S., Oikonomou, A., Ali, I., Ditkofsky, N., Pakkal, M., and Ballyk, B. (2019). Virtual reality and cardiac anatomy: Exploring immersive three‐dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education. *Clinical Anatomy*, 32(2), 238-243.

Moro, C., Phelps, C., Redmond, P., and Stromberga, Z. (2021). HoloLens and mobile augmented reality in medical and health science education: A randomised controlled trial. *British Journal of Educational Technology*, 52(2), 680-694.

Nuanmeesri, S. (2018). The Augmented Reality for Teaching Thai Students about the Human Heart. *International Journal of Emerging Technologies in Learning*, 13(6), 203-213.

Piumsomboon, T., Altimira, D., Kim, H., Clark, A., Lee, G., & Billinghurst, M. (2014, September). Grasp-Shell vs gesture-speech: A comparison of direct and indirect natural interaction techniques in augmented reality. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 73-82). IEEE.

Romli, R. and Wazir, F. N. H. B. M. (2021, July). AR Heart: A Development of Healthcare Informative Application using Augmented Reality. *Journal of Physics: Conference Series*, 1962(1), 012065.

Rosni, N. S., Kadir, Z. A., Mohamed Noor, M. N. M., Abdul Rahman, Z. H., and Bakar, N. A. (2020). Development of mobile markerless augmented reality for cardiovascular system in anatomy and physiology courses in physiotherapy education. In *14th International Conference on Ubiquitous Information Management and Communication (IMCOM), 2020*, pp. 1-5, doi: 10.1109/IMCOM48794.2020.9001692.

Safadel, P. and White, D. (2019). Facilitating molecular biology teaching by using Augmented Reality (AR) and Protein Data Bank (PDB). *TechTrends*, 63(2), 188-193.

Samosky, J. T., Nelson, D. A., Wang, B., Bregman, R., Hosmer, A., Mikulis, B., and Weaver, R. (2012, February). BodyExplorerAR: enhancing a mannequin medical simulator with sensing and projective augmented reality for exploring dynamic anatomy and physiology. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, pp. 263-270.

Venkatesan, M., Mohan, H., Ryan, J. R., Schürch, C. M., Nolan, G. P., Frakes, D. H., and Coskun, A. F. (2021). Virtual and augmented reality for biomedical applications. *Cell Reports Medicine*, 2(7), 100348.

Wainman, B., Pukas, G., Wolak, L., Mohanraj, S., Lamb, J., and Norman, G. R. (2020). The critical role of stereopsis in virtual and mixed reality learning environments. *Anatomical Sciences Education*, 13(3), 401-412.