Using Holograms to Engage Young People with Anatomy

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1.1 Abstract

As the need for STEM professionals continues to grow, encouraging young people into STEM fields is crucial. Technology is an efficient means to engage young audiences with learning, and recent advances in 3D visualisation technologies have impacted the approach to teaching many STEM subjects, including anatomy. Anatomy can be a challenging subject to teach children, and the use of novel digital visualisation technologies have been shown to help engage children with the subject material and improve knowledge acquisition.

The use of 3D holograms as an educational tool has recently begun to be explored. Hologram technology enables the creation of engaging content that provides the viewer with a 3-dimensional experience that can be seen directly with the naked eye. Without the need for headsets, more people can view and interact with the presented visualisations at once and the potential for user side effects which can arise with the use of headsets is removed. These features may make holography particularly beneficial in a range of environments, such as educational settings.

Although holographic technology shows great potential within anatomy education, cost has been identified as one of the main barriers to its use. As such, the development of cost-effective holographic approaches could help to remove the current financial barriers to this novel educational resource.

This project utilised innovative visualisation methods to develop a hologram-based anatomy application suitable for educational environments, which allows young audiences to interact with 3D anatomical models using a voice command system. This application runs on an easily reproducible, cost-effective holographic viewer, also developed during this project. These developments represent a step towards increased accessibility of holographic projection in anatomical education, with the aim of enhancing the engagement of young audiences with anatomy.

Key words: Anatomy, Education, Holograms, 3D visualisation, Cardiovascular system

1.2 Introduction

Technology can be a very efficient means to encourage student engagement, and the incorporation of novel 3-dimensional visualisation technologies has been shown to help engage young people with a variety of biomedical topics, including anatomy. Technology does not have to be expensive to be effective, however many cutting-edge technological approaches, come with a large price tag. The development of cost-effective approaches to biomedical visualisation helps to make these novel approaches available to a wider audience, removing financial barriers to access and thereby increasing the impact they can have.

The aim of this project was to create a cost-effective holographic projection system to facilitate the viewing of a library of anatomical structures as 3D holograms for educational use, presented as a holographic Anatomy application with simple user interface design that enables interactions with the 3D anatomical structures. This aim was achieved through the development of the HoloAnatomy app and HoloViewer, an easily reproducible tabletop hologram viewing device suitable for use in semi-permanent locations, such as the classroom or public engagement environments.

1.3 Background context

As the requirement for science, technology, engineering and maths (STEM) professionals continues to grow (DeJarnette, 2012), there is a clear need to encourage young people into STEM fields. However, a decline in student interest in STEM subjects has been observed, with fewer students choosing to pursue studies in these areas (Osborne, Simon and Collins, 2003; Osborne and Dillon, 2008; Hofstein, Eilks and Bybee, 2011; Sokolowska *et al.*, 2014; Caulfeils, 2018; Sims, Simmonds and Jackson, 2019). Research exploring different approaches to promote STEM to students and encourage their engagement with these fields has demonstrated that early exposure to STEM subjects is a key way to encourage young people into STEM careers (DeJarnette, 2012; Blotnicky *et al.*, 2018).

Anatomy can be a challenging subject to teach to children (Sotelo-Castro and Becerra, 2020) and incorporating novel educational resources alongside more traditional teaching pedagogies can help engage students in this area.

1.3.1 The Use of 3D Digital Technologies to Teach Biomedical Subjects

One way to get students involved in STEM is through the use of novel learning approaches, and the recent advances in 3D digital technologies, especially visualisation technologies, has impacted the approach to teaching many biomedical subjects, including anatomy.

Augmented reality (AR) is a visualisation technology that overlays digital elements, such as 3D models, on top of the real world, 'augmenting' what the user can see and interact with, and over the past decade a range of AR applications have been developed to support teaching. Interestingly, biology-focused applications make up the bulk of the science-focused educational AR apps currently available (Sirakaya and Alsancak Sirakaya, 2018). Educational AR applications have now been developed for a wide range of biological fields, including: general biology (Erbas and Demirer, 2019; Weng *et al.*, 2020), ecosystem science (Kamarainen *et al.*, 2013), molecular biology (Safadel and White, 2019), metabolism (Barrow *et al.*, 2019), and anatomy (Chien, Chen and Jeng, 2010; Nuanmeesri, 2018; Sotelo-Castro and Becerra, 2020). These AR technologies have been shown to not only increase student satisfaction with course material and delivery methods and increase students learning enjoyment, but also to improve student learning outcomes (Kamarainen *et al.*, 2013; Nuanmeesri, 2018; Barrow *et al.*, 2019; Erbas and Demirer, 2019; Safadel and White, 2019).

A study by Barrow *et al* (2019) looked at the use of an AR application in teaching metabolism to undergraduate university students. It was found that the use of AR helped to motivate all study participants to understand the subject matter included, with 58% of students agreeing that the app enhanced their learning (Barrow *et al.*, 2019). The ability to present something to the user that is otherwise not readily visible is a key feature many of novel digital visualisation technologies currently being used for life sciences education, including AR applications, and interestingly, 92% of participants in the Barrow study stated that they felt "*being able to "see" abstracts concepts*" (p11, Barrow *et al.*, 2019) helped their learning.

Human Body AR is an anatomy-focused AR application that was developed by a team at the National University of Saint Augustine, Peru. The app covers basic anatomy of the human body and is aimed at elementary school students (6-12 years old), allowing them to label and interact with cartoon representations of the body and 3D organ models using the AR system. Most children gave the app a "good" usability rating in initial usability tests (Sotelo-Castro and Becerra, 2020). Elementary students have also been shown to readily accept new AR-based teaching methods for human heart anatomy, with the AR app found to improve students' knowledge of the subject matter covered (Nuanmeesri, 2018). Together, these studies indicate that even primary school aged students are able to positively interact with advanced digital visualisation technologies.

Alongside the use of AR, virtual reality (VR) has also begun to be utilised for teaching within the life sciences. VR is a visualisation technique in which the user is fully immersed in an interactive, computer-generated digital environment. *Immunology VR* is an immersive educational virtual reality application, which is being developed by group from Virginia Polytechnic Institute and State University. The application is still at the prototype stage, but it aims to help students to better understand complex immunological concepts, while also increasing student engagement and motivation (Zhang, Bowman and Jones, 2019). Initial user feedback has been positive, with participants stating that the application "*helped with learning*", while the immunology visualisations "*connected the concept with visual representations*" (Zhang, Bowman and Jones, 2019, both p.422), indicating that the use of this 3D technology could be beneficial in teaching biological subjects.

VR-based education applications have also been developed for use outside of the classroom. The Stanford *Virtual Heart Project* is an immersive VR app designed to teach patients and their families, as well as medical trainees, about congenital heart defects (Dorman, 2017). The app includes virtual hearts displaying over 20 of the most common congenital defects (Cunha, 2020), helping users to better understand these conditions and how they can be treated. Users are able to interact with the virtual hearts using a VR headset and handheld controllers, allowing them to explore both their external features and inner workings, by “teleporting” inside the heart.

3D visualisation technologies have also been shown to particularly help support students in their grasp of subjects that rely on the understanding of complex 3D structures (Best, 2016; Cai, Wang and Chiang, 2014), such as anatomy. The inclusion of cadaver-based dissection is a traditional practice included in many advanced anatomy classes (i.e., post-secondary level), and is intended to help students become familiar with the 3D arrangements of anatomical structures. This practice, however, is not always possible, and newer learning approaches are being introduced to support traditional dissection classes. A range of digital technologies are currently utilized for anatomy teaching, with the inclusion of novel digital 3D visualisation technologies, such as AR and mixed reality, providing an innovative route to allow students to experience the 3D enquiry that dissection promotes. AR and mixed reality approaches have been shown to be better at engaging and motivating learners compared to traditional teaching methods (Gnanasegaram, Leung and Beyea, 2020) and to increasing students understanding of the topics covered (Zafar and Zachar, 2020), with a number of anatomy applications currently under development (Chien, Chen and Jeng, 2010; Gnanasegaram, Leung and Beyea, 2020; Maniam et al., 2020; Zafar and Zachar, 2020; Kumar, Pandey and Rahman, 2021). These studies indicate that anatomy-based educational 3D visualisation resources can help facilitate student learning in an effective way.

One such resource is *HoloHuman*, a mixed-reality anatomy application that works using the Microsoft HoloLens (*HoloHuman*, 2018) and allows users to interact with highly detailed 3D models of the human body. Evaluation of *HoloHuman* as an educational tool shows that almost half the dentistry students who used the app said *HoloHuman* improved their understanding of anatomy and helped them to feel more confident in their anatomy skills, while the majority of students felt that using *HoloHuman* would help their learning (87.5% of participants either agreed or strongly agreed) (Zafar and Zachar, 2020).

A number of other novel mixed-reality applications are also being developed to explore human anatomy, including apps focusing on: the ear (Gnanasegaram, Leung and Beyea, 2020), the face (Kumar, Pandey and Rahman, 2021), the skull (McJunkin *et al.*, 2018; Maniam *et al.*, 2020), the breast (Yong *et al.*, 2018), the liver (Pelanis *et al.*, 2020) and the upper and lower limbs (Stojanovska *et al.*, 2020). Although many of these applications are still in early development, initial studies indicate that mixed-reality applications may result in enhanced spatial understanding of anatomical structures (Gnanasegaram, Leung and Beyea, 2020; Pelanis *et al.*, 2020) and increased learner engagement and motivation (Gnanasegaram, Leung and Beyea, 2020), compared to other approaches. Medical students who either undertook traditional cadaveric dissection or used a mixed-reality application have been shown to perform equally well on post-treatment musculoskeletal anatomy exams, regardless of the learning approach employed (Stojanovska *et al.*, 2020).

These studies demonstrate that learning approaches that incorporate digital 3D technologies to teach complex biomedical concepts can be beneficial to students' learning experience, both in terms of knowledge acquisition and student engagement. One such 3D visualisation technology that is now being explored for its educational use is that of digital holographic projection.

1.3.2 The Use of Holograms in Anatomy Education

Holographic projection is a visualisation technique that enables viewing of digital objects in 3-demensions, through the creation of holograms. A hologram is a virtual 3D image of an object, created using light interference and diffraction, that preserves the depth, distance and displacement of the original object or model (Jeong and Jeong, 2005).

A key feature of holography is that holographic representations are actual 3D images, rather than 2D representations of a 3-dimensional object. This means that the viewer does not need to wear specialised headsets or eyewear to see the hologram and its associated depth cues, they can instead be seen in 3D directly with the naked eye. As such, multiple viewers can interact with the same holographic scene in real time, meaning viewing numbers are not limited by the number of headsets available. In educational settings this feature may be beneficial, enabling instructors and students to use the same resource thereby helping to communicate 3D information to students more easily and effectively, while also potentially helping to keep costs lower as a single hologram viewer can be shared by a group of individuals. Additionally, the use of AR and VR visualisation headsets is known to cause a number of user side effects including eyestrain, headaches, fatigue, nausea and dizziness (Hughes *et al.*, 2020; Saredakis *et al.*, 2020), which can impacts users interaction with these technologies. In contrast, no mention of hologram associated side-effects could be found in any of the holography literature investigated. Furthermore, in the current COVID-19 climate, the need to share a headset, which is worn over the face, in order to view a visualisation, now presents a whole new set of hygiene-based challenges and limitations. By using holographic projections, there are no headsets to disinfect between users, helping to remove any potential cross-contamination worries.

Although a ‘true’ hologram is one in which a genuine 3D image is created, in common parlance the term ‘hologram’ is often used to describe visualisations that are not true holographic projections, but those that appear to float in mid-air. For example, applications that use Microsoft’s HoloLens are generally considered to be ‘holographic applications’, however the HoloLens is technically a mixed reality system, requiring a headset to view the resultant visualisations (*HoloLens 2*, 2021).

Pepper’s Ghost illusions are also commonly referred to as holograms, due to the look of the visualisations created, although they do not technically fall into the category of ‘true’ holograms. A Pepper’s Ghost illusion is created by reflecting a 2-dimensional image off of a clear, angled surface, such as a pane of glass, with the resultant optical illusion appearing to float in mid-air behind the surface. Due to their perceived location in physical space, these images appear to the viewer as being 3D holograms, although the resultant projection is in actuality a 2D replication of the original image.

The use of the Pepper’s Ghost illusion was made popular in the in the 19th century where it was used in theatre performances (Burdekin, 2015). The technique was pioneered by John Henry Pepper and usually involved reflecting an image of a brightly lit actor, who was positioned off-stage, to create ghostly apparitions of them on stage, which could be seen by the audience (Burdekin, 2015). Pepper’s Ghost illusions are still utilized in modern theatre productions, however contemporary productions typically rely on the projection of digital visuals (Kaufman, 2006; Farivar, 2012; Williams, 2015), rather than reflections of hidden actors.

A current ‘holographic’ display system that in fact utilizes Pepper’s Ghost illusions is the Dreamoc range of displays from Realfiction (*Holographic displays*, 2021). Although these displays are advertised as “3D holographic displays”, the system relies on projected images that are reflected off a specially coated glass pane, creating the illusion of a 'free-floating' hologram. Interestingly, when digital 3D models and graphics are used with this system it is almost impossible to tell that the resultant visualisations are also not fully 3-dimensional.

Whether using true holographic projection or a floating 'hologram', the use of these visualisation techniques enable the creation of engaging content that provides the viewer with a seemingly 3D experience, whether targeted at advertising (*HYPERVSN*, 2021; *Eye-Catching Retail Campaigns*, 2021), personal use (*Looking Glass Factory*, 2021) or educational settings (*Atlas*, 2021).

1.3.3 The Use of Holograms in Anatomy Education

The use of 3D holograms in anatomy education can help create novel learning approaches where active learning is encouraged, and the potential educational benefits of holography have been discussed for many years (Satava and Jones, 1998; Gorman *et al.*, 2000). Compared to other digital visualisation technologies, however, holographic displays for biomedical and anatomical education are still in their early stages (Hackett and Proctor, 2016), although the application of holographic technology within this area has recently begun to be explored (Hackett, 2013; *Giant hologram gives training extra dimension*, 2016; *Voxgram images for education*, 2021; Hackett and Proctor, 2018).

Early explorations into using holograms for anatomical education included simple visualisations of human anatomy based on data from the *Visible Human Data Set* (Portoni *et al.*, 2000), which could be viewed without a headset or specialised eyewear and had up to eight different views. Although the final image resolution and animation speeds were limited in these visualisations, more recent work has continued to build on these early achievements. In 2013, an autostereoscopic display was created with greatly improved image resolution that could be used to view complex static 3D models (Abildgaard *et al.*, 2010). As a test of principle, neuroradiologists were asked to identify arteries on a 3D model created from intracranial magnetic resonance angiogram, using either the display or a 2D equivalent and the results compared. With the 3D display, 74% of arterial markings were correctly identified by participants, compared to only 57% on the 2D display (Abildgaard *et al.*, 2010).

The use of holography in cardiac anatomy education has also been explored. Work by M. Hackett (2013) has shown that participants who used holograms to study cardiac anatomy demonstrated better spatial awareness and a greater general anatomical knowledge of the material covered, compared to a control group using 2D printed handouts. Additionally, the hologram-based study group performed significantly better on a knowledge post-test, with the use of holograms also associated with a decreased cognitive load compared to those using the printed material (Hackett, 2013). Further work by Hackett and Proctor (2018) has continued to investigate the potential benefits of holograms in cardiac anatomy. Nursing students were given either a holographic cardiac anatomy model, a non-holographic version of the 3D model, or a 2D printed equivalent to use for self-directed study. Students who studied with the holographic model preformed significantly better on a post-treatment knowledge test compared to the other study approaches, and again reported significantly lower cognitive load compared to those using the 2D print material (Hackett and Proctor, 2018). These results indicate that holograms are a cognitively efficient learning method that can help students' understanding of spatial anatomy, however further research is needed to fully elucidate the impact of this novel learning technology. Nonetheless, commercial enterprises have already begun to develop holographic material for anatomical education.

One such company is Holoxica, who developed *The Human Anatomy Atlas* in partnership with the University of Edinburgh (*Holoxica*, 2021) , which was released in 2016 (Robertson, 2016). *The Human Anatomy Atlas* is a collection of digital 3D holograms based on CT, MRI and Ultrasound data sets, spanning the entire human body. The holograms are viewable on commercially available Light Field Displays (*Looking Glass Factory*, 2021; *Holografika*, 2021), and are comprised of fully annotated anatomical structures that can be explored by the user. The *Atlas* is aimed at university-level students, specifically first and second year medical and anatomy students (*Holoxica creates first holographic 3D human 'atlas'*, 2016). Holoxica have also created holograms for anatomical education of non-specialist audiences, again in partnership with the University of Edinburgh. The display, which is apparently the world's largest anatomical hologram (*Giant hologram gives training extra dimension*, 2016), is situated at the University's Anatomy Museum and is open to viewing by the public. These developments have seen Holoxica named as one of Immerse UK's '21 to Watch' early stage ventures in the field of immersive technology (*UK Immersive Tech: VC Investment Report*, 2021), indicating the level of interest surrounding this novel technology.

1.3.4 Using Low-Cost Holograms to Engage Young Audiences

The use of holograms in secondary and tertiary education is an innovative teaching approach that has been shown to have a number of benefits for student learning and engagement, and so it is not hard to envisage that the use of holography would also have a positive impact on education and engagement for younger audiences.

Studies indicate that primary school-aged children positively interact with advanced 3D technologies, such as AR applications, for anatomy education (Nuanmeesri, 2018; Sotelo-Castro and Becerra, 2020), with the potential use of holography for teaching primary school students also having been investigated. Hoon and Shaharuddin (2019) used holographic projections, including Pepper's Ghost style holograms, for teaching Plant Growth to primary school aged children. Their study reports that students showed a 13.45% increase in their understanding of the topic and that the holograms were able to "*grab the students' interest and attract their attention*". As a result of their experience, the students requested to have holography-based learning incorporating into their usual teaching methods (Hoon and Shaharuddin, 2019). Together, these studies suggest that using advanced 3D visualisation technologies, such as hologram-based applications, for anatomy teaching may be well accepted by primary school children and beneficial to their learning outcomes.

Cost, however, has been identified as one of the main barriers to the use of holographic projection in education (Hackett and Proctor, 2016; Elmarash, Adrah and Eljadi, 2021). The development of low-cost technological approaches to biomedical visualisation helps to remove financial barriers to access these novel approaches, and so by focusing on the use of cost-effective hologram technology for engaging young audiences with anatomy education, it could help make this technology available to a wider audience, increasing its potential impact as an educational tool.

There are currently several low-cost holographic viewing approaches available, however they all have their own drawbacks to use in an educational environment. Simple hologram pyramid viewers that can be used with smartphones enable the user to easily view 4-faced holographic projections are available. However, due to the simultaneous projection of 4 versions of the hologram, the resultant viewing area is very small and therefore not ideal for use with complex 3D models. In a 2017 study looking at using this type of viewer to interact with 3D structures, 87% of participants felt that the 3D hologram display gave a better representation of the structures compared to either rendered 3D models or 2D materials, however it was noted that participants requested larger a hologram display to view the structures on (Sulaiman *et al.*, 2017).

Many do-it-yourself (DIY) tutorials for low-cost hologram viewers for use with both smart phone and tablets can be found online, however these are mostly for pyramid-style viewers that result in small, 4-faced holographic projections. Tutorials for 1-faced smart phone viewers are far less common. This style of simple, frameless viewer gives a larger viewing area compared to a pyramid-style viewer, however, as with most pyramid viewers, it requires low ambient light for the resultant hologram to be visible. As such, these types of viewers are not ideal for use in an educational setting, where turning classroom lighting off or down may not be possible or practical. Additionally, the small size of smartphone-based viewers, whether 4-sided or 1-sided, limits the content that can be displayed as the holograms can be no more than a few centimetres in height, obscuring the detail in models and making text hard to read. Thus, the development and use of larger scale, cost-effective hologram viewers could help to expand the uses of this technology within an educational setting.

Tutorials for larger hologram viewers to be used with computer monitors can also be found online, however these are far less common than those for smart phone hologram viewers, with the majority of these aimed at making an enlarged pyramid style viewer. Although potentially more appropriate than phone-based hologram viewers for a group educational setting due to their increased size, they have other potential drawbacks. As with smartphone pyramid-style viewers, these larger pyramid-style viewers are used to view 4-faced holograms, greatly reducing the viewing area of each holographic image compared to the overall screen size, limiting the amount of content that can be displayed. Additionally, these pyramid-viewers do not have a supporting frame and are used while balanced on top of the projection screen, making them potentially unstable. Tutorials for more elaborate styles of tabletop holographic viewers, such as with a fog-based holographic projection system, require the purchase of a number of different materials and complicated build instructions, with the resultant holograms often unclear and not suitable for displaying detailed 3D models. As such, there is an opening for the creation of a low-cost, simple to construct, tabletop holographic projection system that is suitable for use in an educational setting. Such a viewing system could help to make holograms available to a wider audience and increase the impact they could have within anatomical education, by reducing the barriers to access that currently exist with expensive commercial systems.

1.3.5 Anatomy Education for Young Audiences

In Scotland, children begin to learn anatomy during primary school as part of the ‘Body cells and systems’ theme (Education Scotland, 2010). From ages 6-12, children are expected to develop a more in-depth knowledge of their bodies, with human anatomy becoming a central focus. “*The expectation is that that at least two of the… body systems will be studied*” (p19, Education Scotland, 2017) during these years, with students expected to be able to identify the major components of these systems and describe their functions. As such, this age range is when basic anatomy is first introduced and explored by children, and so when developing novel anatomy resources, it makes sense to target this audience in order to help encourage early exposure and engagement with anatomy.

Although children are introduced to anatomy during their primary school years, there are often still gaps in children’s knowledge of key topics covered during this period. A 2017 study looking at scientific visual literacy in primary school children asked participants to produce an anatomical drawing of the chest. Many children did not know the correct position of the heart or lungs, and almost a quarter of children drew the heart as a ‘valentine cartoon shape’, with only 11.6% able to draw an approximate shape of an actual human heart (García Fernández and Ruiz-Gallardo, 2017). This study indicates that many primary school children still have gaps in their basic knowledge of the location and structure of the heart and lungs, and highlights this an area that could benefit from additional learning resources for children.

1.3.6 Conclusion

Technology is an efficient means to engage the younger generation with learning, and the incorporation of novel 3-dimensional visualisation technologies has been shown to help engage young people with a variety of biomedical topics, including anatomy. Primary school children in Scotland commonly study the anatomy of the circulatory and respiratory systems, however gaps in knowledge of these subjects are widespread, making the heart and cardiovascular system a suitable initial focus for a novel hologram-based educational resource for primary school aged children. This project will develop a holographic anatomy application in combination with a cost-effective hologram viewer with the aim of encouraging engagement of young people with anatomy.

1.4 Methods

1.4.1 Overall Concept

There were two development streams for the project: the development of the HoloAnatomy app, and the development of the tabletop HoloViewer. Figure 1 gives an overview of the workflow followed for their concurrent design and development.

Figure 1. Workflow of the project

1.4.2 HoloViewer

Design

An overall plan for the construction of the tabletop HoloViewer was developed, and a CAD model of the tabletop HoloViewer produced to allow the proportions of the viewer to be defined before prototype construction was undertaken (Figure 2). A 45° angle was chosen for the reflective screen based on those used in commercially available hologram viewing systems, such as the dreamoc™POP3 developed by RealFiction™ (*dreamoc POP3*, 2021).

Figure 2. CAD model of the tabletop HoloViewer.

Prototyping and Development

A prototype was built out of medium-density fibreboard (MDF) (Figure 3), a material that is readily available either online or from most DIY supply stores, can be easily cut using power tools or basic hand tools, and takes paint well. 18mm MDF was used to make sure the HoloViewer was strong enough to support the weight of the computer monitor to be used for the image/model projections.

Figure 3. Tabletop HoloViewer prototype.

Once the basic prototype frame was built, the HoloViewer's functionality was tested to confirm that the prototype was able to display clearly visible holographic projections on the reflective screen as intended (Figure 4). The HoloViewer design was then modified to simplify the build process and minimise the number of materials required, and a final HoloViewer frame built (Figure 5).

Figure 4. Tabletop HoloViewer initial testing.

Figure 5. Final frame for the HoloViewer.

Previous work identified 3mm acrylic sheeting as the optimal thickness for the reflective screen in a similarly sized low-cost hologram viewer (Tsenova, 2017), however after testing, the decision was made to use 2mm acrylic for the current HoloViewer.

Many commercially available Pepper's Ghost hologram viewers contain a backlight to illuminate the area behind the reflective screen (Holographic displays, 2021), which can help to give the illusion of the holographic image floating in mid-air. As such, the inclusion of a backlight into the tabletop HoloViewer was investigated, however the tested lighting system did not enhance the viewing experience, and increased the cost and complexity of the build. As such, the HoloViewer was kept unlit.

1.4.3 HoloAnatomy Application

The HoloAnatomy app was developed for use with the tabletop HoloViewer. The content included was centred on the intended learning outcomes for the heart and cardiovascular system, as outlined in the Curriculum for Excellence (Education Scotland, 2010) for children aged 8-12 years old.

Storyboard

Using the Curriculum for Excellence guidelines, a mind map was put together to explore potential content for the app and ideas from the mind map were developed into an initial storyboard (Figure 6).

Figure 6. Initial storyboard for the HoloAnatomy app.

3D Model Development

Segmentation of Anatomical Structures

Heart, lungs and rib/spine models were segmented from one of the sample data sets provided in 3D Slicer. The models were based on medical datasets so that they would more accurately represent human anatomy.

The threshold paint tool in the Editor module of 3D Slicer was used to segment out the anatomical structures of interest. For the rib/spine model, the paint tool (without threshold applied) was then used to fill in 'gaps' in the rib bones due to the presence of bone marrow (Figures 7, 8 and 9).

Figure 7. Segmentation of the heart.

Figure 8. Segmentation of the lungs.

Figure 9. Segmentation of the ribs, sternum and spine.

Retopology & 3D Modelling

The models segmented from 3D Slicer were then used as the basis for further 3D modelling. The segmented heart and lung models generated from Slicer 3D were imported into 3ds Max and manual re-topology was undertaken, before additional model development (Figures 10 and 11). Due to the complexity of the rib/spine model manual retopology was unfeasible. Instead, the segmented model was imported into ZBrush, and a combination of the *Decimation Master* and *ZRemesher* functions were used to create a reduced-poly rib model (Figure 12).

Figure 10. Heart model re-topology. Top row: heart model as exported from Slicer 3D. Shown as a smooth surface model (right) and with polygons displayed (left). Total polygons: 241,549. Bottom row: heart model after re-topology. Shown as a smooth surface model (right) and with polygons displayed (left). Total polygons: 2,143.

Figure 11. Lung model re-topology. Top row: lung model as exported from Slicer 3D. Shown as a smooth surface model (right) and with polygons displayed (left). Total polygons: 491,326. Bottom row: lung model after re-topology. Shown as a smooth surface model (right) and with polygons displayed (left). Total polygons: 2,708.

Figure 12. Rib model re-topology. Top row: rib model as exported from Slicer 3D. Shown as a smooth surface model (right) and with polygons displayed (left). Total polygons: 476,203. Bottom row: rib model after re-topology. Shown as a smooth surface model (right) and with polygons displayed (left). Total polygons: 22,088.

The low poly models of the heart and lungs were imported into ZBrush for modification and detail addition. For the heart model (Figure 13), smaller vessel branches were removed to leave only the major blood vessels coming from the heart, giving a cleaner and simpler model. The superior vena cava (SVC) and inferior vena cava (IVS) were not segmented in the original model, and the SVC was manually added into the model. For the lung model (Figure 14), indents were added to demarcate the borders of the lobes of the lungs, and the trachea was modified, with detailing of the cartilage rings added.

Figure 13. The heart model (a) as imported into ZBrush, (b) after resolution enhancement, and (c) after additional model refinement and detailing. Final polygon count: 22,725.

Figure 14. The lung model (a) as imported into ZBrush, (b) after resolution enhancement, and (c) after additional model refinement and detailing. Final polygon count: 13,796.

After retopology in ZBrush, the rib model was transferred to 3ds Max and further modelling was undertaken (Figure 15). In the model segmented from 3D Slicer, ribs 9 and 10 were not attached to the costal cartilage leading to the body of the sternum. As such, modifications were made to join the anterior portion of these ribs to the sternum, although no differentiation was made in the model between the bone and cartilage. Additional detail was also added to the sternum to allow differentiation between the manubrium (the superior portion of the sternum) and the body of the sternum.

Figure 15. The rib model (a) as imported into 3ds Max, and (b) after additional model refinement and detailing. *Final polygon count: 25,107*.

Texturing

Once 3D modelling was complete, the models were then textured with the aim of creating models that resembled life-like anatomical structures, but were not full photorealistic reproductions. Autodesk Mudbox was used for surface painting of the heart and lung models, with the *Paint Brush* tool used to create the surface pattern by painting directly onto the models in 3D space. The models and their resultant UV Maps were then transferred to 3ds Max and bump maps added to give surface texture (Figure 16).

Figure 16. Final models after surface painting in Mudbox and bump map addition in 3ds Max for the heart model (left) and lung model (right).

As the rib model was not the main focus of the application, but rather a supporting model, a simplified texturing plan was used: the rib model was assigned a basic surface material in 3ds Max and a simple bump map added to give a surface texture to the final model (Figure 17).

Figure 17. Final rib model after texturing in 3ds Max.

Digital Design

The proposed presentation of the HoloAnatomy app using a Pepper's Ghost style hologram placed limitations on the style and colour choices of the app: a black background is needed so that it will disappear in the final holograph and focus attention on the ‘floating’ model hologram. Due to these stylistic limitations, all UI elements were designed specifically for the HoloAnatomy app, rather than using a pre-existing, available icon set.

Application Development

The HoloAnatomy application was developed using Unity 3D, with assets including 3D models and UI components imported into Unity after development in other software packages. The interactivity of the HoloAnatomy app was coded in Visual Studio Code and a voice control system was implemented to allow users to navigate the application without the need for a physical interaction system, such as a keyboard or mouse. As a backup to the voice control system, an alternate means of keyboard navigation was also included.

Viewing the HoloAnatomy app on the HoloViewer impacts the way in which the application is visualised: projecting the app from the computer display onto the 45° reflective screen results in the final holographic view of the application being flipped (Figure 18). For the correct final orientation, the on-computer app display needs to be both rotated 180° and inverted to correct for resultant the top-to-bottom flip and the left-to-right flip.

Figure 18. HoloAnatomy app orientation as seen on the monitor screen versus the HoloViewer.

1.5 Outcomes

1.5.1 HoloViewer

The final HoloViewer frame was made completely out of 18mm MDF with a 2mm thick acrylic screen, and is unlit (Figure 19 and 20).

Figure 19. Final build of the tabletop HoloViewer.

Figure 20. Final HoloViewer with reflective screen.

1.5.2 HoloAnatomy App

The final HoloAnatomy application focuses on interactive models of 3 anatomical structures: the heart, lungs and rib cage. All app navigation and model interaction can be achieved using the voice control system, including 3-dimensional model manipulation, anatomical labelling of the models and the opening/closing of additional fact boxes.

The first scene to open is the Launch scene, followed by the introduction scene when the user starts the application (Figure 21). From here the user can navigate to the menu scene, where they can choose the anatomical structure they would like to explore: the heart (Figure 22), the lungs (Figure 23), or the ribcage (Figure 24). Each structure has its own interactive scene in which the model can be explored by rotating it any direction in 360°, enabling the user to view anatomical features of model that are not visible from the initial view (Figure 25). To further explore the structure, anatomical labels can be added to the model and these labels will rotate with the model allowing the user to more clearly see which structure is being indicated by the particular label (Figure 26). To find out more about the function of the anatomical structure in the scene, the user can open a Fact Box (Figure 27): there are 10 potential facts that can be displayed for each structure, with a random fact being selected by the application every time the Fact Box is called.

Figure 21. The Launch scene (top) and Introduction scene (bottom) of the HoloAnatomy app

Figure 22. The heart scene on loading

Figure 23. The lung scene on loading

Figure 24. The rib scene on loading

Figure 25. 360° rotation of the heart model using the voice control commands

Figure 26. The lung model with anatomical labels visible while still (top) and while rotating (bottom)

Figure 27. The rib model with a Fact Box displayed

1.5.3 HoloAnatomy App as Viewed on the Tabletop HoloViewer

The HoloAnatomy application is designed to be used on the tabletop HoloViewer, as seen in Figures 28 and 29.

Figure 28. The Menu scene as viewed on the HoloViewer.

Figure 29. The 3D model scenes on the HoloViewer. Left: The Heart scene with labels and rotated. Right: The lung scene with model rotated.

1.6 Reflection & Discussion

1.6.1 Critical Review of the HoloViewer

In line with the original aim, the final HoloViewer is a simple construction, which can be made cheaply, from easily sourced materials. However, a shortcoming of the current viewer design is the reflective screen made from 2mm acrylic. The thickness of this material causes a slight double reflection of the holograms, resulting in a small amount blurring of the images and text displayed. Commercially available Pepper's Ghost projections generally utilise beam splitter mirrors, specialised holographic films, or glass with undisclosed proprietary coatings (*How it Works*, 2021) in order to avoid double reflections. Unfortunately, these options are either very expensive or not available to purchase, and so based on previous work using a low-cost hologram viewer (Tsenova, 2017), clear acrylic was used. To further improve the screen quality different approaches should be investigated, such as using thinner acrylic or acetate sheets (for an overhead projector) supported by some sort of solid frame to supply the required rigidity.

1.6.2 Critical Review of the HoloAnatomy Application

3D Models

Segmentation of the lungs was relatively straightforward, however segmentation of the heart and surrounding vessels was more complex due to their orientations and intricate branching. The cartilage of the ribs did not segment adequately, and so additional modelling was undertaken to improve the formation of the lower ribs.

To enhanced the detail of the models, a normal map could be created from a more detailed model and applied over the lower polygon models. This approach would increase the level of detailed surface texture in 3D models without adding to the polygon count and could be applied in the future to the models to improve the level of detail and accuracy of their surface textures.

Application Content & User Interaction

The original concept for the HoloAnatomy application included animations as well as an additional model of the internal structures of the heart, however there were limited opportunities for the user to interact with the application. During development, the HoloAnatomy app was redesigned to focus primarily on user interaction with the 3D models.

If the app were to be expanded, additional features such as animations could be added to further expand the learning potential of the application.

The 3D models in the application can be interacted with using either the voice control system or the key control system, allowing them to be rotated 360° in any direction and anatomical labels added. These interactive elements work well and offer a way for the user to get a 'hands-on' experience with the material being covered. Additional functionality could be added to allow the user to zoom into the models, providing another layer of interactivity.

As the HoloAnatomy app was designed to be viewed as a hologram, this impacted the potential ways in which the app could be interacted with by users: there is no screen in the HoloViewer capable of touch-screen interaction. A gesture control system was initially considered for the HoloViewer, however after additional research this approach was rejected in favour of a voice control system. Although this method of navigation control was chosen in response to the system requirements, a touch-free control system is also particularly attractive in the current COVID-19 climate. A touch-free system helps to remove any potential cross-contamination worries and allows more users to interact with the technology in a set period of time as there is no need to disinfect equipment between users.

The voice control system works well for the current application, however there are some limitations. In an area with high levels of ambient noise the voice control system may have trouble differentiating a command from the background noise, and there is the potential that not all voices or accents will be sufficiently recognised. To help combat this, the voice control system can be set to different confidence levels for the recognition of words, however a balance needs to be struck so that a voice command will be recognised easily, but will also result in the correct outcome. An effort was made to choose command words that are suitably distinct from each other, helping to make recognition as likely as possible, and certain words are only recognized in specific scenes, to further try to reduce the potential for accidental unwanted outcomes.

1.6.3 Limitations and Future Developments

The major limitation of the HoloViewer build is that the equipment has not undergone group testing, and so conclusions about its usability and ability to engage its target audience cannot be made at this time. Proposed testing plans and the associated documentation have been drawn up, but this testing has not yet been undertaken.

Moving forward, adding a wider range of organs and body systems to the HoloAnatomy application would be a key objective. The current app focuses on elements of the cardiovascular system, however it could be expanded to include other body systems. Having an application that covers all the main anatomical structures studied by primary school children would greatly expand its value as an educational resource. Additional features could also be added, such as short informative animations, anatomical models showing healthy and diseased versions of organs (for example, healthy vs. smokers' lungs), and a quiz feature to encourage users to test their knowledge. Game-based learning has been shown to improve students' knowledge retention and academic achievement, as well as increase their motivation and satisfaction with topics covered (Abdul Jabbar and Felicia, 2015; Turner *et al.*, 2018), and so a quiz feature would be a valuable addition to the app.

1.7 Conclusion

This project has developed a cost-effective holographic projection system suitable for educational environments, alongside a hologram-based anatomy application for children aged 8-12 years old. Innovative visualisation methods were utilised to produce the HoloAnatomy application to enable students to interact with 3D anatomical models using a voice command system. The app can be viewed on the tabletop HoloViewer, which was built using cheap and readily accessible materials and could be easily reproduced by a person with basic DIY skills.

Although these developments have not yet undergone testing, and so conclusions about their usability and target audience engagement cannot be made at this time, they represent a positive step towards the use of low-cost digital holographic projection in anatomical education. With further development, this approach could be a beneficial new educational resource to help encourage the engagement of young people with anatomy in the future.

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