**The Holographic Brain: Interactive Holography for Engaging Young People with Anatomy Education**

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# Abstract

Worldwide, young people’s interest in science, technology, engineering, and mathematics (STEM) education declines around pre-teen and early teenage years. Research shows that belief in one’s own scientific ability likely reinforces scientific ambition and effort, suggesting knowledge acquisition should not be neglected when encouraging scientific engagement. Educational tools harnessing three-dimensional (3D) visualisation technologies can increase engagement with science and facilitate knowledge acquisition, often proving more effective than traditional approaches. These educational tools prove particularly beneficial for anatomy education, as complex 3D structures and spatial relationships can be difficult to visualise and understand when learning from 2D materials. Hologram-based educational tools offer considerable advantages over 3D approaches such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) as they do not require a head-mounted display or handheld equipment. Building upon previous research, this study presents a hologram-based application utilising a Pepper’s Ghost Illusion to educate young people on basic neuroanatomy, implementing gesture control paradigms via the Leap Motion Controller. User testing was conducted with twenty participants aged nine to twelve, assessing knowledge acquisition, usability, motivation, and cognitive load. The application significantly increased neuroanatomy knowledge by a mean of 30.25%, had a usability rating above the benchmark median, was motivating, and imposed low cognitive load. Limitations of this study include a lack of both participant demographic data and comparative data with traditional learning approaches. Applications of the type developed in this study represents a novel way of engaging young people with STEM education, in a manner potentially capable of combating their declining interest.

**Keywords:** Children’s e-learning, anatomy education, Peppers Ghost, hologram, Leap Motion, neuroanatomy

# 1 Introduction

In the UK, there is a growing demand for STEM jobs, a trend predicted to continue for the foreseeable future (EMSI, 2018). Nonetheless, research suggests a worldwide decline of young people’s interest in science, technology, engineering, and mathematics (STEM) education (Finlayson and Roach, 2007; González and Kuenzi, 2012; Potvin and Hasni, 2014; Wilson and Mack, 2014). Should this decline in interest continue, it might exacerbate unsustainable strains on the STEM workforce.

The current Scottish curriculum adopts a non-traditional learning approach, encouraging learning through play, student discussion, and creative thinking (Scottish Government, n.d.). While such approaches are associated with increased engagement and enjoyment of science (Andersen and Andersen, 2017), the curriculum has been criticised for prioritising skills and undermining the importance of foundational knowledge (Priestley and Minty, 2013). The declining Programme for International Student Assessment (PISA) science scores of Scottish adolescents since 2015 (Scottish Government, 2021), support the trend of scientific literacy suffering in student-centred classrooms (Andersen and Andersen, 2017; Oliver et al., 2021). As students’ belief in their scientific ability likely influences effort and scientific ambition (Oliver et al., 2021), knowledge acquisition must be maintained as a fundamental part of educational curricula when tackling the decline in young people’s interest in STEM.

Innovative educational approaches utilising state-of-the-art interactive 3D visualisation technologies such as Extended Reality (XR), a terminology encompassing Virtual Reality (VR), Augmented reality (AR), and Mixed Reality (MR), demonstrably increase motivation and engagement with science while facilitating knowledge acquisition, often proving more effective than conventional approaches (Lu and Liu, 2015a; Yammine and Violato, 2015; Lindgren et al., 2016; Sahin and Yilmaz, 2020; Tilhou et al., 2020; Zhao et al., 2020). Anatomy education particularly benefits from adopting such educational approaches as they permit more comprehensive visualisation of complex anatomical structures and their spatial relationships than 2D materials can (Hackett, 2013; Yammine and Violato, 2015; Hackett and Proctor, 2018a). Holograms are a 3D visualisation technology that are showing significant potential as educational tools (Barkhaya and Halim, 2016), offering considerable advantages over other 3D approaches, employing non-invasive and seamless interfaces. Thus, hologram-based applications may potentially become an effective approach for engaging young people in anatomy education while facilitating knowledge acquisition.

Building upon recent research by Herrington et al. (2022), the work presented here aims to define a suitable methodological and technological framework for an interactive hologram-based application within the limits of commercially available hand-tracking technology. It also aims to produce a hologram-based application to educate young people on basic neuroanatomy, and to determine the application’s usability, impact on cognitive load, and motivational effect on young people while facilitating knowledge acquisition. These aims were achieved by examining the suitability of different interaction modalities for hologram-based applications, designing a user-friendly interface, implementing advanced interaction for holograms, and conducting user testing.

## 1.1 Promoting Young People’s Engagement with Science

Worldwide, young people’s interest in STEM education significantly declines around pre-teen and early teenage years (Finlayson and Roach, 2007; González and Kuenzi, 2012; Potvin and Hasni, 2014; Wilson and Mack, 2014). Potvin and Hasni (2014) noted that motivation, interest, and general attitude towards science and technology particularly declines around the elementary to secondary school transition. The UK is not unscathed by this declining interest. Between 2015 and 2019, children aged nine to twelve showed a 10% drop in interest in STEM (Lamb, 2019). Similarly, the 2019 Young People in Scotland Survey found that the percentage of young people interested in studying a STEM subject dropped 4% between 2017 and 2019 (Hepburn, 2020). The lack of resources and equipment has been highlighted as a potential reason for this decline in interest (Lamb, 2019).

 Engagement with ‘informal’ science (i.e., visits to science centres, science fairs, or museums) at a young age has been associated with greater and sustained interest (Finlayson and Roach, 2007; Potvin and Hasni, 2014; Bonnette et al., 2019). If similar resources for these spaces were to be implemented in schools, comparable outcomes could be expected. This is corroborated by the fact that a decline in STEM interest is less pronounced when teachers adopt a non-traditional pedagogical approach (Vedder-Weiss and Fortus, 2011; Potvin and Hasni, 2014). Effectively, Vedder-Weiss and Fortus (2011) found that schools who adopt a non-traditional, student-centred approach with limited textbook use and student-driven curricula do not see the same decline in scientific interest. This suggests that learning through ‘informal’ approaches by lessening a reliance on textbooks could help combat the declining interest in STEM. Promoting science engagement is crucial to the UK’s economic climate as the growing demand for STEM jobs is predicted to continue surpassing the demand for non-STEM jobs for the foreseeable future (EMSI, 2018). For instance, 35% of Scotland’s workforce were employed in the STEM sector in 2015, with the figure projected to increase by 4% over the following ten years (Weaver et al., 2017). Maintaining this STEM workforce would be unsustainable if the accelerating decline in interest continues.

A longitudinal data analysis found that thirteen-year-olds who expected to have STEM careers were more likely to graduate with a degree in science, (Tai et al., 2006) hence the need to trigger an interest in STEM at an early stage in younger people’s education.

In 2022, to encourage the study of STEM and pursuit of STEM careers, the Scottish government developed the Aye for Ideas campaign – a national STEM engagement endeavour designed to inspire and engage the public with STEM (Scottish Government, 2022). Within this campaign, funded engagement initiatives aimed to boost science learning in schools through science shows and workshops and significant funding was allocated to science centres and festivals in support of informal learning. The campaign aimed to engage and inspire the general public with STEM, regardless of age or background.

## 1.2 Science Curriculum in Scotland

In 2010, The Curriculum for Excellence (CfE) was introduced in Scotland, implementing a student-centred constructivist pedagogical approach (Priestley and Minty, 2013). This diverged from the more traditional and rigid teacher-centred pedagogical approach previously in place. The CfE aimed to improve motivation and engagement of students in their learning. To promote interest in science and facilitate effective learning, the CfE encourages the implementation of approaches that largely emphasise skills development such as active learning through play, student discussion, creative thinking exercises, and appropriate technology use (Scottish Government, n.d.).

Although the departure from the highly regimented previous curriculum was largely welcomed, many teachers maintained that the CfE ‘moved too far in the opposite direction’ (Priestley and Minty, 2013, p. 15), undermining the importance of foundational knowledge in favour of skills.

The Organisation for Economic Co-operation and Development (OECD) Programme for International Student Assessment (PISA) takes place every three years and examines the ability of 15-year-olds to apply their reading, mathematics, and scientific knowledge to a real-life context (Hopfenbeck et al., 2018). Since 2015, the scientific achievement of teenagers in Scotland has fallen according to PISA science scores (Logan, 2021), with students performing significantly worse than they did in 2006, 2009, and 2012 (Scottish Government, 2021). This decline appears to correlate with the introduction of the CfE in 2010. It is possible that the decline in achievement was not seen until 2015 due to the students in the 2012 cohort receiving a far greater deal of their scientific education through the previous more regimented curriculum.

Although there seems to exist a positive association between student-centred learning and enjoyment of science, this approach generally has been reported to have a negative impact on academic achievement (Andersen and Andersen, 2017; Echazarra and Mostafa, 2020; Oliver et al., 2021). A recent report found that the ‘self-efficacy’ of students (belief in one’s scientific ability) is the greatest predictor of academic achievement and is likely to strongly influence effort and scientific ambition (Oliver et al., 2021). Based on this evidence, it could be theorised that the CfE catalysed the declining scientific literacy of Scottish students, resulting in lower self-efficacy that negatively impacts their scientific ambition. This suggests that a complete deviation from a traditional teacher-centred approach is unwise, and a middle-ground between both methods might represent the ‘sweet-spot’ of pedagogical approaches.

Regarding life sciences, students in Scotland aged around nine to twelve (the ages where STEM interest declines most) must be taught at least two of the following organ systems: the respiratory system, the circulatory system, the digestive system, the skeletal system, and the reproductive system (Education Scotland, 2017). Study of the structure and function of the sensory organs, biological inheritance, and microorganisms is also required. Regarding technology, they study digital literacy, and are expected to be able to use digital technologies to collect, organise, and analyse information appropriately (Education Scotland, 2017). Since appropriate use of technology and learning through play are encouraged by the CfE, exploiting digital technologies to teach and engage students in science education presents a logical means of enhancing STEM interest.

## 1.3 The Use of 3D Visualisation Technologies in Science Education

Rapid technological advances in the past decade have resulted in the increased accessibility and affordability of novel 3D visualisation technologies (Ihde, 2009; Venkatesan et al., 2021). This has prompted the increased interest in examining such technologies as educational tools, particularly in the domain of science, due to its mutual relationship with technology (Oliveira et al., 2019). Among others, these technologies include VR, AR, and MR, referred to collectively as extended reality (XR).

In VR the user is immersed in a full digital environment, through for instance a head-mounted display (HMD) able to simulate the sensation of depth within 3D environments through stereopsis (Venkatesan et al., 2021). Interactions from users can be achieved using, among other things, head and hand tracking and/or various types of controllers. Unlike VR, AR merely supplements the user’s environment by overlaying digital elements onto their surroundings, often via a handheld device that facilitates touch interaction with augmented elements (Venkatesan et al., 2021). MR is a hybrid of AR and VR, characterised by the creation of an environment that allows real-time interactions between physical and virtual objects. MR generally requires a HMD and allows direct interaction with virtual elements, however an MR HMD does not completely obscure the user’s physical surroundings (Venkatesan et al., 2021).

The use of XR educational tools for science has the potential to increase engagement and interest, and improve academic performance compared to conventional approaches (Tan and Waugh, 2013; Yammine and Violato, 2014; Lu and Liu, 2015a; Lindgren et al., 2016; Sahin and Yilmaz, 2020; Tilhou et al., 2020; Zhao et al., 2020; Reeves et al., 2021; Baratz et al., 2022a). Incorporating such tools into the school curriculum can potentially contribute to tackling declining academic performance while fostering engagement and enjoyment of science.

### 1.3.1 Life Sciences Education

3D visualisation technologies have been shown to be particularly beneficial in the life sciences. For instance, XR educational tools for molecular biology (Tan and Waugh, 2013; Reeves et al., 2021), plant photosynthesis and respiration (Wildan et al., 2020), human cell biology (Bennett and Saunders, 2019), and physiology (Moro et al., 2021) have positively impacted the learning experience of high school and college students.

To the best of our knowledge, XR educational tools used in primary life sciences are AR-based, mostly due to limited research conducted on primary school students using VR (Freina and Ott, 2015). The main reason for this is that VR headset use is not recommended for children under twelve/thirteen years (Freina and Ott, 2015). The life sciences learning experience of primary school students has been positively impacted by AR-based applications covering a wide range of fields, including marine education (Lu and Liu, 2015b), ecology (Stoyanova et al., 2015), bacteria (Hung, Chen and Huang, 2017), the water cycle (Furió et al., 2015), human anatomy (Samia, 2019) and health education (Seel et al., 2022). Of these studies, those assessing knowledge acquisition found AR approaches did not yield significant improvements compared to traditional approaches (Furió et al., 2015; Lu and Liu, 2015a; Hung et al., 2017). However, one study reports that while AR didn’t improve overall academic achievement, it significantly improved the results of lower academic achievers (Lu and Liu, 2015a).  Although AR-based approaches are often found to be only *as* effective as traditional approaches, such traditional approaches are strongly associated with higher academic achievement compared to student-centred approaches (Oliver et al., 2021).

### 1.3.2 Anatomy Education

Due to the complex 3D nature of anatomical structures and their spatial relationships, understanding anatomy can be particularly difficult when learning from 2D materials such as textbooks (Hackett, 2013; Yammine and Violato, 2015; Hackett and Proctor, 2016). Conceptualising anatomical structures from 2D images requires the mental conversion of these images to 3D representations in working memory. This imposes significantly higher cognitive load compared to being initially presented with 3D representations (Hackett, 2013). Cognitive load can be described simply as the mental effort a task takes (Paas, 1992). Cognitive load is comprised of three components: intrinsic, germane, and extraneous cognitive load (Hackett, 2013). Intrinsic cognitive load relates to the inherent complexity of the educational material itself. Germane cognitive load relates to the effort of translating information from working memory into schemas for long-term memory storage. Extraneous cognitive load is related to how material is presented and should be as low as possible to reduce waste of mental resources on irrelevant information (Hackett, 2013). Anatomy education particularly benefits from 3D visualisation technologies, which have been shown to reduce cognitive load by eliminating the need for mental conversion of 2D images to 3D mental representations, improving factual and spatial knowledge acquisition with high user satisfaction (Yammine and Violato, 2015).

There are numerous commercially available interactive 3D resources for learning anatomy on mobile, tablets, and desktop such as Anatomy.tv, anatomy3datlas.com and Complete Anatomy 2022. 3D Organon VR Anatomy is a commercially available VR anatomy education software (3D Organon, 2022) reported to be a highly effective educational tool by anatomy students (Flaherty et al., 2019). ‘HoloHuman’ is a commercially available MR anatomy application and permits interaction with life-size holographic-appearing anatomical models (Pearson and 3D4Medical Announce the Launch of World’s First Anatomy App for Mixed Reality and HoloLens, 2018). When evaluated by dentistry students, 43.5% claimed it improved their understanding of anatomical structures compared to cadaveric-based learning (Zafar and Zachar, 2020). This suggests that approaches like ‘HoloHuman’ may represent a beneficial adjunct to cadaver-based learning (Yammine and Violato, 2015), or suitable alternative when cadaveric-based learning is not possible, such as in children’s education.

Similarly, AR may also represent an effective adjunct to traditional neuroanatomy teaching, or replacement, for when using cadaveric material is not possible. In a recent study by Kurniawan et al. (2018) both college and secondary school students reported that use of an AR application aided in their anatomy education, with students scoring it most highly on its ability to help with anatomy visualisation and promote interest in learning. A recent meta-analysis of 15 randomised controlled studies concluded that VR-based learning is effective at improving medical student’s anatomy understanding compared to traditional approaches (Zhao et al., 2020). Studies assessing MR-based learning using the HoloLens (an MR HMD) for understanding liver (Pelanis et al., 2020), breast (Baratz et al., 2022b), and ear anatomy (Gnanasegaram et al., 2020) found this approach enhanced the learning experience by better conveying anatomical spatial relationships, aiding learning and teamwork, and being more engaging and motivating than conventional approaches. Furthermore, traditional approaches supplemented by MR-based learning enhanced knowledge retention (Baratz et al., 2022b).

XR educational tools for younger children’s anatomy education are less investigated compared to college students, however, a few studies have demonstrated positive results and potential for integration of these tools into the classroom (Samia, 2019; Sotelo-Castro and Becerra, 2020; Seel et al., 2022). Of these studies, the only one that compared knowledge acquisition with traditional approaches found that learning through VR animations resulted in greater knowledge acquisition (Chaudhary and Khushnood, 2019). Additionally, Seel et al. (2022) reported that using AR to support anatomy education in primary schools lead to high knowledge acquisition, user satisfaction and self-confidence. These studies suggest 3D visualisation technologies have the potential to enhance anatomy education at an early stage.

## 1.4 Holographic Projection for Anatomy Education

One 3D visualisation technology that has not yet been discussed as an educational tool for anatomy are holograms. Holograms display 3D objects that appear to float in space (Shan and Chung, 2020). Holograms can be created through various techniques, but all rely on the interference and refraction of light (Shan and Chung, 2020). Unlike AR and many VR approaches, holograms are non-invasive. They do not require HMDs like VR and MR, avoiding potential dizziness and nausea (Xu et al., 2021), or hand-held devices/controllers to support interactions. The lack of HMDs and handheld equipment make holograms a more hygienic option when multiple students must share equipment. Furthermore, most holograms can be viewed by multiple people at once, a convenience not afforded by VR and MR, and is more cumbersome with AR.

The potential of holograms to enhance anatomy education has been discussed for over 20 years (Satava and Jones, 1998; Gorman et al., 2000). A meta-analysis of their use as educational tools confirmed their educational potential, concluding that they can improve learning experience and enhance understanding (Barkhaya and Halim, 2016).

There are currently several commercially available holographic resources for anatomy visualisation, once such being the ‘Holographic 3D Anatomy Atlas’ prototype developed by Holoxica (Atlas, 2022). This atlas allows the viewer to see through multiple layers of the displayed organs simply by moving their head to alter their view of the hologram. Labelled anatomical 3D models can be viewed as holograms on their ‘3D Looking Glass’ displays from Holoxica’s HoloViewer application (Atlas, 2022). The HOLOSCOPE is another commercially available holographic system designed for use in clinical environments, allowing users to directly interact with holograms of medical images (Medical Holography™, 2022).

Multiple studies have assessed the use of holograms utilising stereoscopy as educational tools for anatomy (Portoni et al., 2000; Ilgner et al., 2006; Christopher et al., 2013; Barkhaya and Halim, 2016; Hackett and Proctor, 2018b). An early study examining the efficacy of holograms as educational tools found that the depth information they provided improved medical students’ understanding of anatomical spatial relations compared to a 2D approach (Ilgner et al., 2006). Hackett (2013) and Hackett and Proctor (2018b) compared hologram-based learning with traditional approaches for teaching cardiac anatomy to nursing students and found that holograms better facilitated knowledge acquisition. Both studies also found that studying with holograms reduced cognitive load compared to studying with 2D images. This cognitive load decrease was reported to be statistically significant by Hackett and Proctor (2018).

Pepper’s Ghost is an illusionary technique that creates holographic-appearing displays (Patel and Bhalodiya, 2019; Shan and Chung, 2020) and, though not true holograms, they will be referred to as such for the purpose of this research (Fig. 1). This technique was popularised in theatre productions in London in the 1860s and is based on the refraction of light with glass at an inclined angle (Shan and Chung, 2020).

Multiple holographic applications based on Pepper’s Ghost for anatomy education have been developed, with gesture-based interaction being a common feature (Chang and Lai, 2018; Huang et al., 2018; Patel and Bhalodiya, 2019). Nursing students who used one such application to learn cardiovascular physiology found that the interactive hologram increased enjoyment, was a more efficient way of learning, and helped them visualise abstract information (Chang and Lai, 2018). Huang et al. (2018) developed a similar application incorporating voice descriptions of organs and permitting organ rotation and scaling through gesture control. College students who tested this application gave positive feedback and felt that such an application could improve learning outcomes compared to traditional approaches (Huang et al., 2018). However, there are a lack of studies comparing knowledge acquisition from hologram-based applications with traditional approaches.

Although applications utilising Pepper’s Ghost illusion for children’s anatomy education have been developed (Herrington et al., 2022) or are under development (Supli, 2021), to the knowledge of the author, no study has assessed the efficacy of such a tool for enhancing children’s anatomy education. However, it has been reported that primary school children enjoy learning through such holograms (Ngiik Hoon and Shaharuddin, 2019). A study examining the use of a holographic animation to teach children about plant growth found that it facilitated knowledge acquisition, with 72% of participants test scores improving after watching the animation (Ngiik Hoon and Shaharuddin, 2019). Based on this evidence, it could be suggested that a hologram-based application utilising Pepper’s Ghost illusion could be an effective educational tool for teaching anatomy to primary school students.

# 2 Aims and Objectives

To tackle the declining interest in STEM there is a need for educational resources that actively engage students with science while facilitating knowledge acquisition, particularly in student-centred classrooms where scientific literacy can suffer. Students aged between nine and twelve years could especially benefit from such resources as the decline in STEM interest is most prominent in this demographic. 3D visualisation technologies are particularly useful in anatomy education, with hologram-based applications offering significant advantages over other 3D approaches. However, while hologram-based applications show significant potential as educational tools, their efficacy has not yet been explored in children’s anatomy education.

As neuroanatomy is not covered by the CfE, it represents a suitable topic for a hologram-based application tested by primary school-aged children in Scotland, due to their likely similar and limited initial understanding of it, permitting an accurate measure of knowledge acquisition. This topic would also relate to the study of sensory organs.

Building upon the recent research by Herrington et al. (2022) this research aimed to design and develop a hologram-based application for teaching basic neuroanatomy to young adolescents. This research first defined an intuitive interaction framework for hologram-based applications before the application was designed and developed. These aims were achieved through the following objectives.

1) Explore the suitability of different interaction modalities for hologram-based applications.

2) Design a user-friendly interface for hologram display.

3) Implement advanced interaction for holograms.

4) Create 3D anatomical models suitable for a young audience.

5) Undertake user-testing with a cohort of nine to twelve-year-olds and collect and analyse data regarding user experience and knowledge acquisition.

6) Draw conclusions regarding the suitability of hologram-based applications for educating and engaging young people with anatomy.

# 3 Materials and Methods

## 3.1 Materials

The software, hardware, and data used in the design and development of the application, along with their purpose of use, are outlined below in Table 1, Table 2, and Table 3 respectively.

**Table 1** Software used in this research

|  |  |  |
| --- | --- | --- |
| **Software** | **Publisher** | **Use** |
| **Unity (game engine) - Simple English Wikipedia, the free encyclopedia****Unity** | Unity Technologies<https://unity.com/> | Application development  |
| **Visual Studio Code** | Microsoft<https://code.visualstudio.com/> | Scripting in C# |
| **Logo  Description automatically generated****3D Slicer** | 3D slicer<https://www.slicer.org/> | Indirect Volume Rendering of anatomical structures from medical datasets |
| **ZBrush logo and symbol, meaning, history, PNG****ZBrush** | Pixologic Inc<https://pixologic.com/>  | 3D Model refinement and texturing |
| **Icon  Description automatically generated****3DS Max** | Autodesk, Inc.<https://www.autodesk.co.uk/products/3ds-max/overview> | 3D model creation and UV unwrapping |
| **Microsoft Apps****Paint 3D** | Microsoft<https://apps.microsoft.com/store/detail/paint-3d/> | Storyboard creation |
| **Adobe Illustrator - Wikipedia****Adobe Illustrator** | Adobe, Inc.<https://www.adobe.com/uk/products/illustrator.html>  | 2D asset creation |
| **Logo  Description automatically generated****Adobe Audition** | Adobe, Inc.<https://www.adobe.com/uk/products/audition.html>  |  Audio file editing |
| **upload.wikimedia.org/wikipedia/commons/thumb/c/...****Adobe After Effects** | Adobe, Inc.<https://www.adobe.com/uk/products/aftereffects.html>  | Demonstration video editing |
| **Adobe Color CC | Software Reviews & Alternatives****Adobe Color** | Adobe, Inc.<https://color.adobe.com/>  | Colour palette creation with colour blindness generator |
| **Icon  Description automatically generated****Microsoft Excel** | Microsoft<https://www.microsoft.com/en-us/microsoft-365/excel> | Data visualisation |
| **PSPP Logo - GNU Project - Free Software Foundation (FSF)****PSPP** | GNU Project[PSPP - GNU Project - Free Software Foundation](https://www.gnu.org/software/pspp/) | Statistical analysis |
| **Figma's new icon****Figma** | Figma, Inc<https://www.figma.com/>  | 2D asset and moodboard creation |
| **Logo  Description automatically generated****Miro** | Miro<https://miro.com/>  | Storyboard notation |
| **Digital and IT training | Jisc****Jisc** | Jisc<https://www.jisc.ac.uk/>  | Survey creation  |

**Table 2** Hardware used in this research

|  |  |  |
| --- | --- | --- |
| **Hardware** | **Company** | **Use** |
| **A picture containing clipart  Description automatically generated****ASUS VivoBook 15 X515JA** | ASUSTek Computer Inc.<https://www.asus.com/uk/> | Laptop used to design and develop the application |
| **A picture containing text, sign, clipart  Description automatically generated****Pixel 6** | Google<https://store.google.com/product/pixel_6?pli=1&hl=en-GB> | Device used for voice-over and demonstration video recording |
| **A screenshot of a computer  Description automatically generated with low confidence****Leap Motion Controller** | Ultraleap<https://www.ultraleap.com/> | Device used to achieve hand-tracking and gesture control |
| **Microsoft surface (model)** | Microsoft<https://www.microsoft.com/en-gb/surface>  | Device used for drawing storyboard elements |
| **Logo  Description automatically generated****Iiyama ProLite E2473HDS Monitor****Dimensions:****Monitor: 556 x 346 mm****Display: 523 x 294 mm** | Iiyama <https://iiyama.com/gl_en/products/prolite-e2473hds-1/>  | Monitor used in HoloViewer |
| **Shape  Description automatically generated with medium confidence****Logitech C270 HD Webcam** | Logitech International S.A.<https://www.logitech.com/>  | Webcam used with application |
| **Samsung logo and symbol, meaning, history, PNG****Samsung Galaxy Tab S5e** | The Samsung Group<https://www.samsung.com/uk/support/model/SM-T720NZSABTU/>  | Tablet used for participant data entry |

**Table 3** Data sources used in this research

|  |  |  |
| --- | --- | --- |
| **Data** | **Source** | **Use** |
| **A picture containing diagram  Description automatically generated****‘Visible Human Male’ CT dataset** | National Library of Medicine<https://www.nlm.nih.gov/>  | Dataset used for indirect volume rendering of skull |
| **Cannot select a volume in Input lung CT manual - Support - 3D Slicer  Community****‘MRHead’ MRI dataset** | 3D Slicer<https://www.slicer.org/> | Dataset used for indirect volume rendering of brain |
| **Gallery Image 4****GORE 1 - PBR0162** | Textures.com<https://www.textures.com/>  | Albedo used for polypainting brain texture |
| **A picture containing icon  Description automatically generated****AR Techni Font** | Dafont.com<https://www.dafont.com/>  | Application font |
| **9-year-old Human Child Skull** | Bone Clones, Inc.[**https://boneclones.com/product/9-year-old-human-child-skull-BC-277**](https://boneclones.com/product/9-year-old-human-child-skull-BC-277) | Reference image used for skull model |
| **Fig 1.2 - The lobes of the cerebral cortex.** | TeachMeAnatomy<https://teachmeanatomy.info/>  | Reference image used for segmenting brain lobes |
| **Definition of vertebral column - NCI Dictionary of Cancer Terms - NCI** | National Institute of Cancer<https://www.cancer.gov/> | Reference image used for spinal cord model |
| **A picture containing person, dark  Description automatically generated****Boy Kid Child Body Base Mesh** | Sketchfab<https://sketchfab.com/>  | 3D model used in animation scene |
| **Holo Cam Webcam** | <https://unityassets4free.com/>  | Unity plugin used for Window on World |
| **Highlight Plus** | <https://unityassetcollection.com/>  | Shader used on application models |
| **A picture containing light, green  Description automatically generated****HologramShader** | <https://github.com/andydbc/HologramShader> | Shader used in scanning scene of application |
| **Scanner Sci-Fi** | Freesound<https://freesound.org/people/smokinghotdog/sounds/584918/> | ‘Scanning’ audio used in application |
| **UI Interface Positive** | Freesound<https://freesound.org/people/JavierZumer/sounds/257227/>  | ‘Scan complete’ audio used in application |
| **Christmas Reveal Tones** | Mixkit<https://mixkit.co/free-sound-effects/sparkle/>  | ‘Celebration’ audio used in application |
| **Message Pop Alert** | Mixkit<https://mixkit.co/free-sound-effects/pop/>  | ‘Selection’ and ‘panel close’ audio feedback used in application |

## 3.2 Methods

### 3.2.1 Design and Development Workflow

The workflow of the application design and development is detailed in Fig. 2.

### 3.2.2 Concept

This research project builds upon previous research from Herrington et al. (2022), who built the HoloViewer, a hologram projection platform for engaging young people with anatomy. This research explores interaction paradigms and visual information fixtures beyond those proposed by the HoloViewer. A case study focusing on neuroanatomy is proposed here as it is a suitable subject for examining knowledge acquisition due to the lack of exposure of children to it in primary school in Scotland.

### 3.2.3 Developing Interaction and Display Framework

To determine suitable interaction paradigms and display framework for the application, a series of rapid internal testing iterations were conducted. Further details and testing outcomes are presented in Table 4.

**Table 4** Results of internal testing of interaction and display framework

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Functionality** | **Description** | **Interface** | **Assessment method** | **Outcomes** | **To be used** |
| **Manual rotation of 3D model** | Swiping hand across model’s surface to rotate | Leap Motion  | Swiped hand along X and Y-axis over cube with position locked | **(+)** Functional and intuitive**(-)** Hand models must be visible (virtual embodiment) for accurate interaction | No |
| **Virtual Embodiment** | The user being able to see virtual representations of their hands | Leap Motion | The hands were assigned to a layer that was initially rendered and then not rendered by the camera when interacting with a test scene | **(-)** Visible hands obscured and distracted from application content  | No |
| **Anaglyph 3D** | Generated stereopsis effect achieved by encoding each eye's image using cyan and red filters | YouTube video and anaglyph glasses | 3D anaglyph videos were watched on the HoloViewer using two types of anaglyph glasses | **(-)** The cyan and red did not blend when wearing the glasses and it failed to enhance the 3D effect - potentially due to the double image created by the acrylic screen  | No |
| **Window on World (WoW)** | Skewing the camera’s projection matrix based on the user’s head position allowing the user to view objects at different angles. (Kessenich, Sellers and Shreiner, 2016) | Webcam and Holo Cam Webcam Plugin | Placed 3D objects in a plane representing the screen position and moved around in front of the webcam to view different angles of a cube Sensitivity of movement was altered to find the most accurate calibration. Also tested on HoloViewer display | **(+)** Functional and intuitive **(+)** 3D appearance of the model was increased**(-)** There is lag when the head moves quickly  | Yes |
| **3D button press** | Pressing a 3D button in the scene | Leap Motion and Leap UI Asset | Pressed a 3D button to change the colour of a cube | **(+)** Functional and intuitive**(-)** Virtual embodiment needed for accurate interaction between hand and button. Only intuitive when hand models are visible, which was determined previously to be too distracting | No |
| **3D slider** | Sliding finger along 3D slider in the scene | Leap Motion and Leap UI Asset | Placed finger on 3D slider and moved the slider side-to-side | **(+)** Intuitive**(-)** Difficult to move precisely, particularly without virtual embodiment | No |
| **Ray from fingertip** | Casting a virtual ray outward, originating from the index fingertip, that passes into the scene as a means of interacting with objects it hits in the scene. This is commonly employed in VR applications utilising hand-tracking | Leap Motion | A raycast with a line renderer was sent from the tip of the index finger and 3 capsules were placed on the bottom of the scene spanning its width. A message was printed to the console whenever the ray hit the capsule | **(+)** Functional and intuitive**(-)** Uncomfortable to interact with objects near the camera, particularly objects not near centre of screen when the object is on the same side of the screen as the hand pointing | No |
| **Cursor control with pointing index finger** | Controlling a cursor with index finger that casts a ray into the scene along the Z-axis, only when index finger pointed | Leap Motion | A cursor was made visible, and its position controlled by the index finger when the index finger was pointed | **(-)** Inaccurate detection of index finger pointing gesture  | No |
| **Cursor control without gesture** | Controlling a cursor with index finger that casts a ray into the scene along the Z-axis | Leap Motion | A cursor was always visible, and its position controlled by the index finger without the need for a specific gesture | **(+)** Accurate and intuitive cursor control | Yes |
| **Limits of hand-tracking** | The limit on the screen that the index finger position is accurately tracked. | Leap Motion | The index finger controlling a cursor was moved around each area of the screen  | **(-)** Less accurate tracking in top corners of screen, and bottom corners to a lesser extent | - |
| **Pinch to select** | Making a pinch gesture with index finger and thumb to select object cursor is over when Leap Motion Controller is placed on table  | Leap Motion | A message to the console was printed each time a pinch gesture was detectedGesture detection was tested in all regions of the screen | **(+)** Intuitive **(-)** Inaccurate gesture detection when hand not close to/directly above Leap Motion Controller in desktop mode (when Leap Motion is placed on table beneath hands), and screentop mode (when placed on screentop facing user).  | No |
| **Grab to select** | Making a fist to select object cursor is over | Leap Motion | A message was printed to the console saying the name of the object the cursor was over when a grab/fist gesture was made with the same hand controlling the cursor | **(+)** Gesture accurately detected **(-)** Gesture often moved the cursor off the object | No |
| **Thumbs up to select** | Making ‘thumbs up gesture’ with opposite hand to that controlling the cursor to select object cursor is over | Leap Motion | A message was printed to the console when the thumbs up gesture was detected | **(-)** Inaccurate gesture detection, likely due to rest of hand occluding thumb from Leap Motion sensor | No |
| **Wait to select** | Holding cursor over object for set amount of time to select object | Leap Motion | A text panel was activated when the cursor was held over an object for 1.5 seconds. The object was also highlighted, and a progress ring implemented next to the cursor when testing this interaction to signify that the object could be selected when progress ring is full | **(+)** Functional, accurate and intuitive1.5 seconds was determined to be a suitable amount of wait time | Yes |
| **Grab to close panel** | Making a fist gesture with right-hand to close panel | Leap Motion | A panel was deactivated when a fist/grab gesture was made | **(+)** Functional, accurate and intuitive | Yes |
| **Move fist along X and Y-axes to rotate** | Moving left fist along X-axis to rotate object on its Y-axis and moving left fist along Y-axis to rotate object on its X-axis. | Leap Motion | A cube was rotated on its X or Y-axis when the left first was moved along the Y or X-axis respectively. | **(+)** Functional and intuitive**(-)** Accurate rotation only when movement along a single axis is enabled | Yes |
| **Cursor icon change with gesture change** | Changing cursor icon between fist and open hand icon depending on hand gesture | Leap Motion | The open hand cursor icon was switched to a fist icon when the hand was in a fist  | **(+)** Accurate and gives feedback to users on whether their gesture was detected, this feedback could increase immersion | Yes |
| **Cursor depth scaling** | Scaling the cursor icon based on the depth of the hand within the scene | Leap Motion | Cursor scale was adjusted based on the hand movement on the Z-axis, scaling larger and smaller as it moves towards and away from the HoloViewer | **(+)** Gives impression that the cursor is moving in 3D spaceScaling must be capped at certain points, so cursor never appears distractingly small or large | Yes |

### 3.2.4 Storyboard, Mood board, and Colour Palette

Storyboards outlining the application interactions (Fig. 3) and content (Fig. 4) were created during the design phase. Storyboard images were created in Paint 3D and annotated in Miro. A mood board was also created to visualise the application’s desired aesthetic with a futuristic ‘cyberpunk’ theme, to reflect the perceptions many might have of holographic technology.

A six-colour palette was created using Adobe Color (color.adobe.com). Each colour would be assigned to a specific brain region. Considering accessibility, Adobe Colour’s colour blindness simulator and two colour blind people (one with deuteranopia and one with deuteranomaly and protanopia) deemed the palette ‘colour blind safe’ (Fig. 5). Additionally, colour would only be supplemental and never a primary indicator of critical information.

### 3.2.5 3D Model Creation

#### Segmentation using 3D Slicer

3D Slicer was used to perform indirect volume rendering (IDVR) of the skull and brain using open access medical datasets. IDVR is a process where polygonal isosurfaces of anatomical structures are generated based on contour identification, or segmentation. The Visible Human Male CT dataset was used to segment the skull as CT datasets are most suited for visualising dense structures such as bone (van Eijnatten et al., 2018). As part of the nasal bones and the superior aspect of the skull were not captured in this dataset, these were sculpted afterwards. This dataset was cropped to the region of interest, and the Laplacian Sharpening Image Filter was applied to sharpen the skull boundaries, facilitating more accurate boundary detection for segmentation. Segmentations were created using the Segment Editor module. The threshold effect was employed to determine the skull’s intensity range as 200-maximum and perform automatic segmentation. The Eraser tool was used to manually deselect structures not part of the skull and to refine the teeth, while disconnected groups of pixels were removed using the Island Effects tool. Unwanted holes in the segmentation such as those in the orbit walls, sinuses and air pockets within the bone were filled manually with the Paint tool to refine the model surface and prevent unnecessary inner detail when displayed translucently. Using the ‘add selected island’ option in the Island Effects tool, the mandible was appointed as a separate segment, first ensuring there were no connections between the cranium and mandible (Fig. 6).

The open-source MRI dataset provided by 3D Slicer named MRHead was used to create the brain model, as MRI datasets provide good contrast between soft tissues (Wadhwa et al., 2019) such as the brain and surrounding cerebrospinal fluid, which marks the brain tissue boundary. Threshold Filtering was used to define the intensity ranges of the cerebrum, cerebellum, and brainstem and create a rough segmentation of each. These segmentations were refined using the Paint, Eraser, and Island Effects tools. As sucli on the lateral and posterior aspects of the brain lacked definition, they were refined using the Eraser tool. The frontal, temporal, parietal, and occipital lobes of the brain were segmented from the cerebrum selection using the Paint tool with the ‘editable area’ set to ‘Inside Cerebrum’. Consulting a brain diagram reference image ensured accurate lobe boundaries. Displaying the brain semi-transparently would introduce unnecessary detail of inner brain structures for the target audience. If only the outer brain surface is visible to the user, this renders inner brain structure accuracy redundant. Therefore, lobes were segmented with subcortical structures included such that only their outer surface is anatomically accurate, essentially making each lobe a ‘wedge’ of the cerebrum (Fig. 7).

Finally, skull and brain segmentations were exported as models. The Surface Toolbox module was used to reduce model vertex number by 30%, to smooth using the Laplace algorithm, and to remove floating vertices and connect closely adjacent ones using the Connectivity tool. Models were then exported as .obj files.

#### Model Refinement in 3DS Max and ZBrush

Model meshes were inspected in 3DS Max, and any remaining disconnected polygons were manually deleted. Models were exported as .obj files and imported into ZBrush, where holes in the mesh were closed using the Close Holes and Weld Points buttons in the Geometry sub-palette of the Tools palette. To optimise models for real-time rendering it was necessary to reduce the high polygon count and create a simplified and more orderly mesh topology through retopology. A duplicate of each model was created, and ZRemesher was used to retopologise the duplicates.

Using the Half button with ZRemesher, a low polygon (‘low poly’) version of each retopologised model was created. This low poly mesh was subdivided to create a high poly version using the Divide function in the Geometry sub-palette, resulting in a model with multiple subdivisions. Details from the original version of each model were projected onto the retopologised version, which introduced some topology errors that were removed using the Smooth and Standard brushes.

The Standard and Smooth brushes were used to sculpt the apex of the skull and the Standard and Move brushes were used to sculpt the anterior regions of the nasal bones. The skull model was further smoothed and sculpted to create a simpler looking bone surface more suitable for young audiences, and more closely resembling a younger person (Fig. 8). A reference image of a nine-year-old child’s skull was used when refining the skull model. The prominence of the brow ridge and jawline were reduced and smoothed, as these are not as prominent in children before puberty (Marečková et al., 2011; Koudelová et al., 2015).

The Standard and Smooth brushes were also used to refine the brain models, particularly the cerebrum gyri and sulci and the cerebellum folia.

Low poly brain models were exported to 3DS Max for UV map generation as 3DS Max allows more control over this process. The model was then reimported to ZBrush for normal map generation. Brain model textures were generated on the high poly models using Polypaint with the ‘Gore 1’ texture (Table 3) before being exported. Using a low poly model with a high poly texture and a normal map is more power efficient for real-time engines, permitting a high level of detail without straining processing capabilities (Fig. 9).

The skull’s complex 3D nature rendered UV map generation particularly difficult. The low poly skull model was imported to Unity to assess the necessity of a UV map, as high detail was unnecessary for its brief role in the animation scene where it would be translucent. When imported to Unity a normal map was deemed unnecessary, so a UV map was not generated. When a fade material was added to it however, the cranium’s inner layer caused a ‘stacking’ effect, rendering it more opaque than the rest of the cranium, introducing unwanted detail (Fig. 10). As making the cranium solid would resolve this issue, its inner layer was removed in 3DS Max (Fig. 11), and the cranium model re-imported to ZBrush where holes connecting the inner and outer layers (e.g., the foramen magnum) were closed using the Close Holes function (Fig. 12). The model was retopologised again, without the inner cranium layer. Higher detail was achieved with a similar poly count as the previous version, allowing further definition of the teeth with the ‘Standard’ brush (Fig. 13).

Due to the brevity of its appearance in the animation, a simple spinal cord model was created in 3DS Max (Fig. 14).

#### Creation of 3D UI models

3D UI elements were created using TextPlus in 3DS Max in AR Techni font (Fig. 15).

### 3.2.6 2D, Audio, and Video Asset Creation

2D assets such as the panels (Fig. 16), function icons (Fig. 17), cursor icons (Fig. 18), and logo (Fig. 19) were created using Adobe Illustrator. These were developed specifically for the application adhering to the cyberpunk style.

### 3.2.7 Application Development

The application was developed using Unity and Visual Studio Code for C# scripting. Prior to asset creation, a greybox prototype of the application was created to develop the interactions with primitives (Fig. 20). Once the final assets were created, they were imported into Unity to replace the primitives.

#### Leap Motion Interactions

##### Cursor Selection

Navigation through the application is controlled using two cursors that follow the user’s index fingers on the Leap hand models template, which were overlaid onto the hand tracking data provided by the Ultra Leap controller. The cursors interact with the anatomical models and the 3D buttons within the scene. Sample scripts from the Ultraleap SDK informed how to programmatically reference the index fingertips. The transform of each index fingertip was then assigned to a sphere primitive in the Cursor script’s Update function. This approach simplified debugging during the development process and allowed clearer visualisation of lost tracking of the hands. Once cursor interactions were achieved, the mesh renderers of the spheres were disabled and Leap hands were placed in a layer not rendered by the camera. The world space position of the spheres was then translated to screen space using the Camera.WorldToScreenPoint method and a cursor sprite was assigned to these screen space transforms, to visually represent the user’s hand positions. For cursor interaction with world space elements, the Camera.ScreenPointToRay method was used to cast a ray into the scene from each cursor and a Raycast function facilitated collision detection. Interactable 3D objects were tagged ‘RayInteractable’ and given collider components. When a cursor is positioned over a world space object, the object is hit with the corresponding cursor ray. When hit, the emission component of the object material is enabled producing a highlighted appearance, and a 1.5 second timer is launched using the Time.deltaTime method. This timer is visually represented by a ‘progress ring’ beside the cursor, which is a sprite of a circle that’s fill amount is defined as a percentage of the timer’s progress towards 100% fill. On its completion, the method GameObject.SendMessage calls a method on the hit object, invoking an event specific to that object via UnityEvent.Invoke. This method of object selection enabled simple and efficient function calling, eliminating the need for scripting straightforward methods such as GameObject.SetActive. If the cursor leaves the object before timer completion, its material’s emission is disabled, and the timer reset. Although cursors can simultaneously highlight, a timer will not begin for a cursor if one has already begun on the other, preventing simultaneous selections. To give the appearance of depth to cursor movement, the cursor sprites scale was adjusted according to the index finger’s position on the world space z-axis, decreasing when it is moved towards the HoloViewer, and increasing when it is moved towards the user. Maximum and minimum X and Y values were assigned to scaling, preventing dramatic cursor scale changes.

##### Fist Rotation

Making a fist with the left-hand and moving it side-to-side rotates the brain model on its y-axis. The ExtendedFingerDetection script from the Leap SDK calls the FistRotation script’s ToggleRotation function when no fingers are extended on the left-hand and replaces the open hand cursor sprite with a fist sprite. The FistRotation script’s Rotate function operates through similar logic as the cursor scaling code. When the left-hand is no longer in a fist, the cursor sprite reverts to the open hand sprite, and ToggleRotation function is called again. The rotation value of the labels is set to the negative of the brain’s rotation, ensuring that they always face the user.

##### Grab to Close

The Leap SDK ExtendedFingerDetection script detects when a fist is made with the right-hand, closing any open panels and associated buttons, and reactivating any objects that were inactivated when the panel was opened.

#### Window on World Paradigm

The Holo Cam Webcam plugin was used to track the user's face and skew the camera’s projection matrix according to their point of view. This concept was first described in 1965 (Sutherland, 1965), later coined ‘Window on World’ (WoW) (Bishop and Fuchs, 1992) and popularised among others by Johnny Chung Lee in 2008[[1]](#footnote-1). The Sensibility variable was assigned a value of 3 so the projection matrix adjustment was subtle, giving the brain a ‘natural’ 3D appearance. The 3D models were positioned in a plane defined by the script that represents the “screen’s position” in virtual space, ensuring only the rotation of the objects appeared to adjust and never the position (Fig. 21).

#### Screen Inversion

As the HoloViewer inverts the x and y-axis of the displayed image, the application must accommodate this. The y-axis was simply inverted by flipping the HoloViewer’s monitor while the x-axis was inverted within the application. In the main menu and introductory scenes without WoW, a ScreenFlip script[[2]](#footnote-2) is assigned to the camera to flip the x-axis. However, this script was not suitable when the Holo Cam Webcam plugin was applied to the main camera, so a different approach was taken by editing the plugin’s HolographicCamera script. As screen space canvas elements were unaffected by this code, they were flipped manually through bulk selection and setting their x-axis scale to -1.

#### Scene Architecture

The scene architecture and movement permitted between scenes of the application is presented in Fig. 22.

#### Scene Unlock Manager

The SceneUnlockManager script permits interaction with the ‘Discover’ and ‘Quiz’ buttons in the main menu only after their respective scenes have been reached through completion of the prior scenes. Once these buttons are ‘unlocked’, they are assigned the tag ‘RayInteractable’, their material changed, and the locked icon beside them deactivated. The DontDestroyOnLoad method[[3]](#footnote-3) was called in the Awake function so that it was carried through each scene of the application to ensure that the GameObject the script is assigned to would never be duplicated.

#### Scanning Scene

To achieve the ‘scanning’ effect, the HologramShader (Table 3) was applied to a transparent plane placed in front of a plane on which the webcam texture was rendered. A Coroutine was employed to change the text on the panel in the scene from ‘Scanning user…’ to ‘Scan Complete’ after seven seconds, before loading the next scene.

#### Animation Scene

In the animation scene, the camera’s position, the rotation of the body’s parent object, and the materials and highlights on its children (the body, brain, skull, and spinal cord) were animated in Unity. For the animation, a version of the cerebrum split into separate hemispheres is briefly enabled to facilitate their respective highlighting.

#### Discover Scene

In the ‘Discover’ scene, selection of a brain region triggers several functions through the Events System. These include triggering the brain animating to the side, fact panel activation, badge ‘unlocking’ (switching the locked sprite for the function icon sprite), label deactivation, and HighlightPlus shader (Table 3) deactivation on non-selected brain regions. The Event System of the ExtendedFingerDetection script controlled fact panel closing, triggering the brain animating to the centre of the screen, reactivating the HighlightPlus shader on all brain regions, and reactivating labels when a right-hand fist was detected. A bool for each brain region was set to true when the respective brain region was selected and when all were true, the ‘Test your knowledge’ button was activated.

#### Quiz

The QuizManager script was adapted from a tutorial by one of the authors, though some of it was not suitable for this project. Due to the structure of the quiz scene and interaction paradigm of the application, the randomisation of questions was reworked. Question randomisation was achieved by correlating a number 0 – 5 with each quiz question. A random number within this range was generated and cross-referenced with a list of asked questions. If the question was already asked, a number was generated again recursively until a new number was generated. It is then added to the list, preventing that question from being asked again. The quiz is structured as two parts of six questions, the first part asking the user to label the brain regions, and the second part involving matching functions to brain regions.

### 2.2.8 HoloViewer Adjustments

To improve the HoloViewer display, some structural adjustments were made. The 2mm acrylic screen was replaced with a 3mm rear anti-reflection coated glass. This glass significantly reduces the double image, with a darker and less pronounced duplicate of the image (Fig. 23). Wood panels were added to the sides of the HoloViewer to reduce light entering its sides, enhancing the 3D appearance of the models (Fig. 24).

# 4 Results

This chapter presents the application developed in this research. It consists of a main menu, an introductory sequence simulating a scan of the user followed by an animation about the brain, a scene where users can interact with and learn about each brain region, and culminates in a quiz scene. A recorded demonstration of the application can be found at (<https://youtu.be/jV4MGAej71M>).

## 4.1 Splash Screen

A custom splash screen is used in addition to the default Unity splash screen (Fig. 25).

## 4.2 Interactions

Moving the cursor over an interactive element displays a progress ring indicating to the user that it will be selected when full. If a panel has been opened, making a fist with the right-hand closes it. Both interactions are accompanied by audio feedback. The ‘Help’ button activates a panel (Fig. 26) containing a brief instruction video that reminds the user of the application controls (Fig. 27). While the ‘Help’ panel is open, objects behind it are deactivated, preventing accidental selections.

The ‘Quiz’ and ‘Discover’ scenes have additional functionality permitting the user to rotate the brain by making a fist with their left-hand and moving it side-to-side (Fig. 27), and WoW which allows them to view the brain from different perspectives according to their head position.

## 4.3 Main Menu

The user is first brought to the main menu, displaying the application logo and buttons leading to the ‘Introduction’, ‘Discover’, and ‘Quiz’ scenes respectively. Initially, the ‘Discover’ and ‘Quiz’ buttons are locked, preventing their selection until the scenes leading to them are completed (Fig. 28). ‘Help’ and ‘Quit’ buttons are also present. The ‘Quit’ button deactivates all main menu buttons and opens a quit panel prompting the user to confirm their choice (Fig. 29). Selecting ‘Yes’ quits the application while the ‘No’ button, or closing the panel reactivates all buttons.

## 4.4 Scanning Scene

Upward-moving, glowing blue lines presented over a webcam display of the user's face and sci-fi inspired ‘scanning’ audio simulates a scan of the user (Fig. 30a). After seven seconds the ‘scan’ is complete, a ‘ping’ audio plays, and the animation begins (Fig. 30b).

## 4.5 Animation Scene

The 70-second-long animation, guided by voice-over, initially displays the ‘scan data’ - a body, skull, and brain (Fig. 31). The body fades out and the skull and brain rotate 360°. The skull then fades out and each brain region is introduced with the respective region highlighted. When the animation ends, the ‘Replay’, ‘Discover more’, ‘Help’ and ‘Home’ buttons are activated, allowing the user to choose what to do next (Fig. 32). Selecting ‘Discover more’ leads to the discover scene. If the animation is replayed, the ‘Discover more’ button remains active, allowing the user to move on without needing to wait for it to finish (Fig. 33).

## 4.6 Discover Scene

The discover scene allows the user to explore the brain regions (cerebellum, brainstem, frontal, temporal, parietal, and occipital lobes), learning their names and functions. A labelled brain model is presented in the centre of the scene, with each region glowing a different colour. ‘Help’, ‘Home’, ‘Labels’, and ‘Reset’ buttons are presented on the right of the screen. The ‘Labels’ button toggles labels on/off, and the ‘Reset’ button resets the brain’s rotation (Fig. 34). The user must select each brain region to ‘unlock’ its function (Fig. 35a). When a region is selected, labels are deactivated, the brain animates to the left side of the screen and the glow is removed from all brain regions except the selected region (Fig. 35b). Simultaneously, a panel with text and voice-over describing the region’s function is activated. The voice-over gives extra detail not examinable in the quiz, such as a ‘fun fact’, or further explanation about the function. When this is closed, the brain animates back to the centre of the screen, labels and the ‘Label’ button are reactivated, and all brain regions regain their glow. The locked icon beneath the label of the selected region is replaced with a ‘badge’ representing its function/s (Fig. 35c). When each brain region has been explored, a ‘Test your knowledge’ button leading to the quiz scene is activated (Fig. 36).

## 4.7 Quiz Scene

The quiz scene tests the user on the names and function of each brain region. The scene retains a similar layout to the ‘Discover’ scene, with the quiz questions displayed above the brain (Fig. 37). The first six quiz questions require the user to label the brain by selecting the region asked in the question. When the brain is fully labelled, a panel informs the user they are halfway through the quiz (Fig. 38). The further six questions require the user to match a function with the corresponding brain region, and with each correct answer, the badge/s depicting the region’s function is added to the label (Fig. 39). Positive and negative feedback is given via short audio clips for correct and incorrect answers respectively. The quiz question changes when correctly answered. On quiz completion, a short animation of the brain ‘jumping’ and spinning is played accompanied by a ‘celebration’ audio, and a panel congratulates the user (Fig. 40). The application then returns to the main menu.

# 5 Evaluation

This chapter discusses the experimental evaluation of the application developed in this research. As discussed in the introduction, while hologram-based applications show significant potential as educational tools for anatomy, their efficacy has not yet been investigated for children’s anatomy education. Hence, The Holographic Brain application was developed, and user tested.

The research question for this evaluation was:

Can a hologram-based application promote an engaging learning experience while facilitating knowledge acquisition in young people?

## 5.1 Methods

### 5.1.1 Participants

Twenty participants aged between nine and twelve were recruited at the Glasgow Science Centre. Demographic information was not collected from participants. The Glasgow Science Centre is a paid attraction; hence all participants represented a demographic capable of affording this excursion.

### 5.1.2Ethics

Ethical approval for this research was granted by the Learning and Teaching Committee of The Glasgow School of Art.

### 5.1.3 Apparatus

The application was run on a PC connected to a monitor installed on top of the HoloViewer. Using a Command™ Strip, a Leap Motion Controller was secured to the table that the HoloViewer was placed on, and a webcam was placed on top of the HoloViewer. Logitech speakers were placed on either side of the HoloViewer and angled towards the participant. A height-adjustable desk chair for participants to sit in while using the application facilitated optimal positioning for viewing, webcam capture, and hand tracking (Fig. 41). The online survey tool JISC was utilised for survey administration and a Samsung S5e Tablet was used for experimental data collection and demonstration video display.

### 5.1.4 Experimental Procedure

Potential participants and their parent/guardian were first given a participant information sheet informing about the study. Consent forms were then signed by the researcher, parent/guardian, and child if they wished to participate.

Participants took a pre-test of ten multiple choice questions to assess their initial neuroanatomy knowledge, before being shown a demonstration video explaining how to navigate the application. Next, participants were given unlimited time to use the application, while the researcher sat nearby assisting with application navigation and answering any questions if necessary. When participants finished using the application, they completed the post-test which consisted of the same questions of the pre-test but reordered. Finally, participants completed a thirty-three question user experience survey.

The user experience survey included ten questions on usability (System Usability Scale (SUS)) (Brooke, 1996), twelve questions on motivation (Reduced Instructional Materials Motivation Survey (RIMMS)) (Loorbach et al., 2015), ten questions on cognitive load (Cognitive Load Scale (CLS)) (Leppink et al., 2013) and a textbox for additional comments. Where possible, survey questions were reworded in a simpler way to facilitate participants comprehension, while retaining the same meaning. Each question was paired with a five-point Likert scale where response options ‘strongly disagree’ to ‘strongly agree’ were illustrated with emojis.

Small stickers with the application’s logo were awarded to each participant.

### 5.1.5 Data Analysis

All collected data were exported to Microsoft Excel for analysis. Statistical tests were conducted using PSPP.

Knowledge acquisition was measured by comparing pre-test and post-test results using a two-tailed paired t-test to assess statistical significance. A Pearson correlation test was carried out to assess the linear relationships between pre-test and post-test data and interpreted according to the ‘Rule of Thumb’ outlined by Mukaka (2012) (Table 5).

**Table 5** Interpretation of Pearson's correlation coefficient. Adapted from (Mukaka, 2012)

|  |  |
| --- | --- |
| **Correlation coefficient** | **Interpretation** |
| .90 to 1.00 (−.90 to −1.00) | Very high positive (negative) correlation |
| .70 to .90 (−.70 to −.90) | High positive (negative) correlation |
| .50 to .70 (−.50 to −.70) | Moderate positive (negative) correlation |
| .30 to .50 (−.30 to −.50) | Low positive (negative) correlation |
| .00 to .30 (.00 to −.30) | Negligible correlation |

SUS scores were calculated according to guidelines by Brooke (1996). First, each response option was converted to a number from 0-4 with 0 being “strongly disagree” and 4 being “strongly agree”. As odd and even-numbered questions are phrased positively and negatively respectively, they are treated differently during analysis (Table 6). The mean SUS score was calculated and compared with an SUS grading/rating system (Bangor et al., 2009).

**Table 6** SUS analysis (Brooke, 1996)

|  |  |
| --- | --- |
| X | (Sum of all odd-numbered question responses) - 5 |
| Y | 25 – (Sum of all even-numbered question responses) |
| Score out of 40 | X+Y |
| SUS Score (out of 100) | (X+Y) \* 2.5 |

The RIMMS examines four constructs – attention, relevance, confidence, and satisfaction, each construct assessed in three questions, towards motivational design assessment (Loorbach et al., 2015). See Table 7 for each construct’s definition. Question responses were first converted to a number from 1-5, with 1 being “strongly disagree” and 5 being “strongly agree”. Means and standard deviations were calculated using Microsoft Excel.

**Table 7** Explanation of RIMMS constructs according to (Keller, 2010a, p44-45)

|  |  |
| --- | --- |
| **RIMMS Construct** | **Explanation** |
| Attention | The stimulation and maintenance of the user’s interest |
| Relevance | The familiarity or relevance of the content to the user’s goals. |
| Confidence | The confidence of the user in their ability to learn the content |
| Satisfaction | The user’s satisfaction with the learning experience |

The CLS differentially measures the three components of cognitive load, with three questions assessing intrinsic, three assessing extraneous, and four assessing germane load (Leppink et al., 2013). Intrinsic load refers to the content’s innate complexity, extraneous load to the content’s presentation, and germane to the ability to transfer learned content from working to long-term memory (Hackett, 2013). Although CLS responses are generally reported on a ten-point Likert scale, this study adopted a five-point Likert scale to be more manageable for children, and consistent with previous survey response options. Responses were first converted to a number/score from 1-5 in the same manner as RIMMS data. The germane load score was subtracted from six for interpretation consistency as these questions were phrased negatively, unlike the rest. Means and standard deviations were calculated using Microsoft Excel.

Finally, Pearson correlation coefficients were calculated to assess the linear relationships between the dependent variable and interpreted according to Table 5.

## 5.3 Results

### 5.3.1 Knowledge Acquisition

Normal distribution of pre-test and post-test scores were confirmed with a Shapiro-Wilk test, permitting statistical analysis with a paired t-test. Paired t-test results (*t*(19) = - 5.56, *p* < 0.001) revealed that post-test scores (*M* = 7.35, *SD* = 2.25) were significantly higher than pre-test scores (*M* = 4.10, *SD* = 2.07) with an increase of 30.25% in post-test scores (Fig. 42). No significant correlation was found between pre-test and post-test scores (*r*(18) = .273, *p* = .243).

### 5.3.2 Usability

The application received a score of 69.5 on the SUS, 1.5 points higher than the benchmark median score of 68, (Fig. 43). The application placed in the ~55th percentile, achieved a high marginal acceptability rating, a letter grade of C, and an ‘OK’ adjective rating according to Sauro (2018) (Fig. 44).

### 5.3.3 Motivation

The application scored highly on each RIMMS construct of attention (*M* = 4.32, *SD* = 0.66), relevance (*M* = 4.10, *SD* = 0.78), confidence (*M* = 4.45, *SD* = 0.62), and satisfaction (*M* = 4.42, *SD* = 0.63) (out of a maximum score of 5) (Fig. 45). There was a low positive correlation that approached significance between post-test score and mean RIMMS score (*r*(18) = .43, *p* = .058).

### 5.3.4 Cognitive Load

The application scored quite low on each cognitive load component, namely intrinsic load (*M* = 2.13, *SD* = 1.08), extraneous load (*M* = 1.78*, SD* = 0.99), and germane load (*M* = 1.48, *SD* = 0.64)(out of a possible minimum score of 1) (Fig. 46).

### 5.3.5 Correlations between measures

SUS score had a moderate positive correlation with mean RIMMS score (*r*(18) = .614, *p* = 0.004 (Fig. 47a) and post-test score (*r*(18) = .625, *p* = 0.003) (Fig. 47b). It had a low negative correlation with extraneous load, that did not reach statistical significance (*r*(18) = -.393, *p* = 0.087).

There was a positive moderate correlation between SUS score and attention (*r*(18) = .501, *p* = 0.024) (Fig. 48a), relevance (*r*(18) = .635, *p* = 0.003) (Fig. 48b), and confidence (*r*(18) = .0.534, *p* = 0.015) (Fig. 48c). There was a low positive correlation between SUS and satisfaction that approached, but did not reach significance (*r*(18) = .431, *p* = 0.058) (Fig. 48d).

Germane load was moderately negatively correlated with attention (*r*(18) = -.694, *p* = 0.001) (Fig. 49a), relevance (*r*(18) = -.573, *p* = 0.008) (Fig. 49b), and confidence (*r*(10) = -.628, *p* = 0.003) (Fig. 49c). No other correlations were found between cognitive load components and constructs measured by RIMMS, nor were any noteworthy correlations observed between any other measures.

### 5.3.6 Comments

Eight participants provided qualitative feedback, with seven of the eight comments being positive. The negative comment stated that the use of hand gestures was “*difficult compared to mouse and keyboard*”. Conversely, two others stated the app was “*easy to use*”. Further comments described the app as “*very engaging*”, “*helpful*”, “*good*”, and “*well designed*”, while two participants remarked on how much they learned. Regarding content difficulty, one participant commented that it “*wasn’t too hard or too easy*”.

It was anecdotally reported by three guardians that it was the longest they had seen the participant sit down and concentrate on one thing, remarking on their perceived attention to the application.

# 6 Discussion

This research aimed to create and assess a hologram-based application for educating young people on basic neuroanatomy. As aforementioned, combatting the declining interest in STEM calls for the development of educational resources that promote engagement and knowledge acquisition, particularly for student-centred classrooms where scientific achievement may suffer. The application was aimed at children aged nine to twelve, the demographic where this declining interest is most prominent. While 3D visualisation technologies like hologram-based applications demonstrably benefit anatomy education, their potential for children’s anatomy education has not been investigated to the knowledge of the authors. Hence, ‘The Holographic Brain’ was developed seeking to foster engagement while maintaining a focus on knowledge acquisition.

## 6.1 Design and Development Process

A significant challenge encountered when creating this application was the development of the interaction paradigm using the Leap Motion Controller, which had considerable limitations to its hand-tracking and gesture recognition capabilities. As pinching is a popular VR gesture used for selection (Mutasim et al., 2021), this interaction paradigm was tested. However, the gesture was only reliably detected in a narrow area directly above the sensors, despite attempting implementation using the pinch gesture detector provided with the Gemini V5 SDK and using script developed by the author. Intuitive gestures such as pointing and giving a thumbs-up were tested but were also poorly detected by the Leap Motion. Detection of ‘touch screen-like’ gestures such as tapping and swiping was provided in the V2 SDK but has been discontinued. Reverting to this legacy SDK from the V5 SDK was considered, however, this was deemed unfeasible as it would lead to a significant decline in hand-tracking performance and accuracy. Although the final interaction paradigm was effective, iterative testing of interactions was a time-consuming and frustrating process.

Regarding the display framework of the application, a moderate perceived 3D sensation was achieved through the holographic display and WoW effect. While the WoW effect, controlled by point of view tracking from a webcam, enhanced the 3D appearance of the models, there was noticeable lag when adjusting the camera’s projection matrix, particularly when head movements were not slow or subtle. Anaglyph 3D was re-tested after acquiring rear anti-reflection coated glass, but the slight remaining double ghost image still interfered with the stereoscopic effect. On reflection, another display paradigm which could have led to increased 3D appearance of the models would be the incorporation of ‘real-world’ objects with the holographic projection. This could potentially blur the line between real solid and projected 3D objects.

The ‘scanning scene’ prior to the animation was added as a fun ‘gimmick’ that could increase fun and potentially immersion if the user believed the scan was real. From observation during user testing, participants were highly entertained by this scene, with some gasping in surprise when the ‘scan’ began, and some asking if the models in the animation scene were from their scan. As the Leap Motion was detected as another webcam, difficulty was encountered in assigning the correct webcam to render on the plane during development of this scene. This issue initially went unnoticed as the scene did not require the Leap Motion to be connected during its development. Although the solution to this problem required coding a relatively simple ‘if’ statement to specify the correct camera, the cause of the problem took time to deduce.

The gamification aspect of the application which consisted of unlocking labels and badges succeeded in encouraging participants to explore each brain region from observation during user testing by increasing the playfulness. It also provided a visual representation of the participants’ progress through the quiz scene, which may have increased motivation to complete the quiz. Further gamification of the application, such as some required interactions to prompt the next animation stage to proceed may increase engagement in the animation scene, as it was longer than originally anticipated at 70 seconds.

## 6.2 Experimental Key Findings

The aim of user testing this application was to determine its efficacy to engage young people in active learning and facilitate knowledge acquisition. The results indicate that the application is of ‘OK’ usability; creates a motivating learning experience; imposes a low cognitive load; and facilitates knowledge acquisition. These findings strongly suggest that the application succeeds in engaging young people in an effective learning experience.

### 6.2.1 Demographic

Although demographic data was not collected from participants, the narrow range of nine to twelve years suggests that impact of age differences on experimental data would likely be minor. The tester demographic represented those able to afford the Glasgow Science Centre entrance ticket prices, which may not include be accessible to disadvantaged children. The lack of demographic data somewhat limits the level of analysis that can be carried out on the experimental data.

### 6.2.2 Knowledge Acquisition

The highly significant 30.25% improvement in post-test scores compared to pre-test scores verifies that the application facilitates knowledge acquisition. Two participants’ comments claiming that they ‘learnt so much’ and ‘learned a lot’ support this trend. Interestingly, no significant linear correlation between pre-test and post-test scores was found, meaning that those who scored lowest on the pre-test were not necessarily more likely to score lowest on the post-test, and vice versa. This suggests that knowledge acquisition was not uniform between individuals. As no correlation was found between the delta value (the difference between pre-test and post-test) and attention, this may be due to the delta value being skewed by a high score in the pre-test.

Administration of the same quiz to the participants after a set period (e.g., seven days), similar to the experimental design by Bell et al., (2008) and Chittaro and Buttussi (2015) would provide insights on the application’s facilitation of knowledge retention.

### 6.2.3 Usability

The application’s above average SUS score of 69.5, indicates that although the application is moderately easy and intuitive to use due to an effective interaction framework and design, it could still be improved upon. Two similar studies by Garcia-Zapirain et al. (2017) and Al-Khalifa (2017), assessing educational applications utilising the Leap Motion, reported similar SUS scores of 71.11 and 71.1 respectively. Furthermore, studies assessing the usability of non-educational applications using the Leap Motion consistently reported below average SUS scores (Coelho and Verbeek, 2014; Caggianese et al., 2016; Nestorov et al., 2016; Pirker et al., 2017). This suggests that the interaction paradigms provided through the Leap Motion Controller may somewhat limit usability, likely due to similar limitations encountered during this project’s initial interaction testing (e.g., tracking range, gesture recognition failure), rendering the above average SUS score received by this application notable.

Although one participant claimed that “the hand gestures are difficult compared to mouse and keyboard” and others claimed it was “easy” and “very easy” to use, their respective SUS scores did not reflect these comments, highlighting the fact that feedback from children may not be highly reliable (Fuchs, 2008). Measurement of participant interaction times with the application may reveal further insights into participants’ reported usability, as a certain amount of interaction time is necessary for familiarisation with the system.

The three participants who gave the lowest SUS scores, also accounted for three of the four lowest scores on the post-test (scoring 50% or less), suggesting the strong impact usability has on knowledge acquisition. Comparable to the present study, similar correlations between usability and motivation, and usability and knowledge acquisition have been found in other studies (Meiselwitz and Sadera, 2008; Álvarez-Xochihua et al., 2017). This highlights the impact usability has on important factors of learning experience, prompting the suggestion of a potential experimental framework whereby usability is closely examined and improved upon throughout educational application development.

It should also be noted that this application’s ‘OK’ usability rating did not impede on motivation, cognitive load, or knowledge acquisition.

As prior experience with technology (such as games consoles and tablets) positively impacted SUS score in a similar study (Al-Khalifa, 2017), comparing SUS scores with participant’s level of technology use could reveal a possible correlational relationship, hence the need to collect demographics in further experiments.

### 6.2.4 Motivation

The application scored highly on each construct assessed in the RIMMS (attention, relevance, confidence, and satisfaction), with no construct scoring below 4.1 out of 5, indicating the highly motivating experience provided by the application. As motivation majorly drives engagement (Orji and Vassileva, 2021), these results suggest a high level of engagement with the application. However, the risk of acquiescence bias must be noted as all questions of the RIMMS are phrased positively, meaning that if participants are more likely to acquiesce/agree with statements, this may skew the data positively (Welkenhuysen-Gybels et al., 2003). The slight gamification of the application, whereby elements such as scenes, function icons (‘badges’), and labels were gradually unlocked as the user progressed through the application may have enhanced motivation. Although the near-significant correlation between RIMMS and post-test scores (*p* = 0.058) indicates the positive impact of motivation on learning outcomes, a larger correlation is seen between usability and post-test scores. This implies that while usability is positively correlated with motivation, usability may be the more influential factor regarding learning outcomes. One could speculate that frustration of poor usability may detract from the learning experience, with attention focussing on learning to use the application rather than the content.

### 6.2.5 Cognitive Load

The application imposed moderate intrinsic load (scoring 2.13 out of 5), low extraneous load (scoring 1.78 out of 5), and low germane load (scoring 1.48 out of 5). As intrinsic load refers to the content’s innate complexity (Hackett, 2013), the scoring for this component suggests that participants found application content moderately complex. Despite this, the lower score for germane load (at 1.48 out of 5) which relates to the effort of converting information from working to long-term memory through the creation of schemas (Hackett, 2013), suggests that the application enabled them to learn this content with relative ease. The low score for extraneous load (1.78 out of 5) also suggests that the presentation of the content is conducive to learning. As increased usability of educational tools decreases cognitive load (Hollender et al., 2010), this suggests that the low negative correlation of extrinsic load with usability may not have reached statistical significance due to a low sample size. Furthermore, the lower quality of children’s survey responses (Fuchs, 2008) may also have been a factor in the lack of statistical significance of this correlation.

The moderate negative correlation between germane load and the RIMMS constructs of attention, relevance, and confidence implies the importance of motivational components in processing and converting working to long-term memory through schemas. This finding is supported by Whelan’s (2007) review where it is noted that germane load is frequently linked with motivation as it influences individuals’ effort given to schema formation.

## 6.3 Limitations and Future Research

Although time was a limitation, all scenes and major functionalities proposed in the initial storyboard were achieved in the final application. A later considered feature was voice command, though time restraints prevented its implementation. The option to use voice commands to navigate the application as in the study by Herrington et al. (2022), would increase the accessibility and usability of the application for users who may have difficulty with the gesture control and could be a consideration for further development of the application. However, this may also be a limitation in a noisy environment such as the Glasgow Science Centre where user testing was carried out.

The lack of demographic data collected during user testing was an oversight by the author and limited the analysis that could be carried out to provide further insight on some of the data trends seen. For example, familiarity with technology may likely have played a role in participant’s perceived usability of the application, as was reported by Al-Khalifa (2017) who also developed and tested a children’s educational application utilising the Leap Motion. Collection of participant age and gender data may have allowed deeper analysis of the user testing findings.

Experimental design of future research could include the addition of a control group learning the same information as the test group in a more conventional way (e.g., from a booklet), facilitating comparisons between both learning approaches on knowledge acquisition, motivation, and cognitive load. Additionally, examining knowledge retention from each of these learning approaches after a set period would provide further insight into the efficacy of both approaches for long-term learning. Such an experimental design would permit more substantial evaluation of the application. Further development of the application content could cover more neuroanatomy such as neuron structure and function, as well as other body systems.

# 7 Conclusion

Educational resources harnessing 3D visualisation technologies can enhance young people’s engagement and achievement in science education and present a means of combating their declining interest in STEM. Hologram-based applications have significant advantages over other 3D visualisation technologies; they do not require a HMD or handheld equipment, making them particularly suitable for younger audiences. Anatomy particularly benefits from 3D visualisation, and while evidence shows that hologram-based applications enhance anatomy education, up to the author’s knowledge this has not been investigated in younger audiences.

Hence, this research has developed and assessed a hologram-based application to educate young people on basic neuroanatomy in an engaging manner. Small-scale user testing of the application revealed it provided a motivating learning experience where knowledge acquisition was facilitated with low impact on cognitive load. The results of this pioneering research contribute to the field of Technologically-Enhanced Learning by showing considerable promise for future development of hologram-based applications for young people’s science education. Should further research support these results, hologram-based applications may one day have a place in the classroom as a resource capable of enhancing the engagement, interest, and scientific literacy of students.

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**Fig. 1** Diagram demonstrating how holograms are created through Pepper's Ghost Illusion (El-Gammal, 2020)

**Fig. 2** Design and development workflow

**Fig. 3** Initial storyboard for application interactions

**Fig. 4** Initial storyboard for application content

**Fig. 5** Colour palette with colour blind simulations

**Fig. 6** Segmentation of the skull

**Fig. 7** Segmentation of the brain

**Fig. 8** Before and after smoothing the skull to make it more child-friendly and child-like

**Fig. 9** **a** Low poly version of brain model with 12,140 polygons to be used in application and **b** high poly version of brain model with 683,155 polygons which details were sculpted on, and textures generated on

**Fig. 10** Cranium with fade material in Unity on first import

**Fig. 11** Inner cranium layer highlighted in red

**Fig. 12** Cranium showing foramen magnum after closing holes

**Fig. 13** Final skull model with 9,902 polygons in total

**Fig. 14** Spinal cord with brainstem model

**Fig. 15** UI models made using TextPlus in 3DS Max

**Fig. 16** UI panel

**Fig. 17** Function icons and locked icon

**Fig. 18** Development of cursor icon

**Fig. 19** Application logo

**Fig. 20** Prototype scene for interaction development

**Fig. 21** Scene view showing the placement of the brain model in the ‘screen’ plane

**Fig. 22** Flow of application scenes. Black arrows represent manual and purple arrows represent automatic scene changes

**Fig. 23** **a** Double image with acrylic screen and **b** with rear anti-reflection coated glass

**Fig. 24** **a** HoloViewer before and **b** after adding wooden side panels

**Fig. 25** Splash screen with Unity to ‘The Holographic Brain’ logo transition

**Fig. 26** Help panel with ‘Play’ button

**Fig. 27** Stills of demonstration video

**Fig. 28** **a** Main menu with locked and **b** unlocked 'Discover' and 'Quiz' scenes

**Fig. 29** Quit panel

**Fig. 30** **a** Scanning scene during ‘scan’ and **b** at ‘scan’ completion. The lead author is pictured in these images and consents to their use in this chapter

**Fig. 31** Stills from the animation scene

**Fig. 32** End of animation

**Fig. 33** Animation replay with 'Discover more' and ‘Home’ button active

**Fig. 34** Rotation of the brain in the discovery scene with **a** labels on and **b** labels off

**Fig. 35** **a** Selection of temporal lobe, **b** result of selecting temporal lobe, and **c** when temporal lobe panel is closed

**Fig. 36** Discover scene with all badges unlocked and 'Test your knowledge' button activated

**Fig. 37** First quiz question with no brain regions labelled

**Fig. 38** Halfway panel of quiz after all labelling questions have been answered

**Fig. 39** Quiz scene halfway through function questions

**Fig. 40** Congratulations panel on quiz completion

**Fig. 41** Experimental set up

**Fig. 42** Pre-test vs. post-test scores. \*\*\**p* < 0.001 versus pre-test. Results expressed as mean ± standard deviation

**Fig. 43** Scatterplot of SUS scores for application. The blue dashed line represents the median benchmark usability score (68), the red dashed line represents the usability score for this application (SUS = 69.5)

**Fig. 44** SUS percentile ranking of application with acceptability, grade, and adjective rating. Grey dashed line represents the benchmark median SUS score, and red dashed line represents the SUS score of this application. Figure adapted from (Sauro, 2018)

**Fig. 45** RIMMS score for each construct. Results expressed as mean ± standard deviation

**Fig. 46** Cognitive load component scores. Results expressed as mean ± standard deviation

**Fig. 47** Scatterplot of **a** SUS score vs. RIMMS score and **b** SUS score vs. Post-test score with line of best fit, Pearson’s correlation coefficient (*r*), and p-value (*p*)

**Fig. 48** Scatterplots of **a** SUS score vs. Attention, **b** SUS score vs. Relevance, **c** SUS score vs. Confidence, and **d** SUS score vs. Satisfaction with line of best fit, Pearson's correlation coefficient (*r*), and p-value (*p*)

**Fig. 49** Scatterplots of **a** Germane load vs. Attention, **b** Germane load vs. Relevance, and **c** Germane load vs. Confidence with line of best fit, Pearson's correlation coefficient (*r*), and p-value (*p*)

1. https://www.youtube.com/watch?v=Jd3-eiid-Uw. [↑](#footnote-ref-1)
2. Code for this script was taken from answers.unity.com (https://answers.unity.com/questions/20337/flipmirror-camera.html?childToView=20365#answer-20365). [↑](#footnote-ref-2)
3. Code for this method was taken from answers.unity.com (https://answers.unity.com/questions/982403/how-to-not-duplicate-game-objects-on-dontdestroyon.html). [↑](#footnote-ref-3)