The Digital Dolphin: Are 3D mobile based and interactive models a useful aid to volunteers on stranding schemes learning the basic anatomy and pathology of cetaceans?

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Abstract

Cetacean research is crucially aided by stranding programs, such as the Scottish Marine Animal Stranding Scheme (SMASS). As part of SMASS's activities, it facilitates necropsies on stranded marine mammals that cannot be returned to the sea. Marine mammals can become stranded for multiple reasons and necropsies provide researchers with valuable information about seasonal distribution, feeding habits, and cause of death. In Scotland, necropsies are typically performed by experienced veterinary pathologists supported by a network of volunteer citizen scientists. To successfully sample visceral organs, volunteers must be properly trained in the anatomy and pathology of cetaceans.

Although there have been numerous examples of 3D models being used to teach human or veterinary anatomy, few interactive and digitally accessible resources exist to support education of cetacean anatomy. Within this project, an intuitive app with a series of 3D models illustrating the anatomies of the thoracic cavity of a harbour porpoise has been developed to provide anatomical data on a digital format accessible on mobile devices in a field situation. Pilot testing was conducted and the results were highly rated in usability and user experience. Minor refinements to the models are recommended to increase accuracy in future product development. This pilot testing confirmed that there is a demand for 3d digital models of cetacean anatomy to support stranding network volunteers.

Keywords

Segmentation
Cetacean
Stranding networks
Veterinary anatomy

Technology
3D learning

1 Introduction

"Cetacean" is a term that refers to the family of aquatic mammals which encompasses dolphins, whales, and porpoises that belong to the infraorder "Cetacea". Key characteristics of Cetacea include their fully aquatic lives, carnivorous diet, and large size. The infraorder can be split into two Parvorder: firstly, there are the Mysticeti or the baleen whales, this category includes animals such as the humpback whale (Megaptera novaeangliae); secondly, there are the Odontoceti or the toothed whales, this category includes animals such as bottlenose dolphin (Tursiops truncatus). Cetaceans are the only mammals that are completely adapted to a fully aquatic life. Breathing must take place on the surface of the water and is facilitated through the blowhole, which is vaguely comparable in function to the nostrils of humans.

This research focused on the anatomy of the harbour porpoise (Phocena ohocena), a cetacean species in the parvorder Odonotceti. Harbour porpoise are the most common cetacean found stranded on Scottish shores, amounting to 49% of all reported strandings in 2019 (Davison et al., 2019).

Strandings are monitored by collaborative organisations throughout the United Kingdom with the Scottish Marine Animal Stranding Scheme (SMASS) being the main organisation collating, collecting and investigating marine animal standings in Scotland. Data collected can aid the understanding of the distribution of and threats and pressures impacting species in UK waters, (SMASS, 2021). These data can also be valuable in predicting the population health of marine species in the ocean, for example the English based Cetacean Stranding Investigation Programme (CSIP) linked the recent rise in humpback whale strandings on British coastlines as indication of species recovery following the commercial whaling moratorium enacted in the mid 1980s (ZSL - Zoological Society of London, 2018). There an increasing public awareness of the requirement to understand marine health, which coupled with greater engagement in citizen science initiatives and widespread permeance of mobile technology, has creating a demand for tools to understand marine environments and ecology.

In order to determine the cause of the stranding, find out how the animal died, and its condition whilst alive, a number of stranded mammals are retrieved for post mortem examination or necropsy (SMASS, 2021). A necropsy is a systematic series of gross observations that provide data on the gross pathology and enable both the cause of death and the significance of disease to be established. Routine samples are taken along the way that are analysed further for parasites, enzymes, antibodies, and histopathology (ZSL - Zoological Society of London, 2018). As the necropsy progresses further inwards, samples are taken from the layer of insulating and energy-storing blubber directly underneath the skin and these samples are examined in histopathology and bacteriology. Following the external layers of skin and blubber, the ribs and intercostal muscles are removed and the internal viscera is examined within the three distinct compartments - thoracic, abdominal, and peritoneal. The organs of the three compartments can be removed as pluck and examined outside of the body cavity or examined in situ.

The lungs and heart are more complicated and interesting anatomies with numerous pathology to consider. Cetaceans are the only mammals that are completely adapted to a fully aquatic life. Breathing must take place on the surface of the water and is facilitated through the blowhole, which is vaguely comparable in function to the nostrils of humans. The respiratory tract in cetaceans is not connected to the mouth and the pharynx is completely separate from the larynx to prevent leakage from the alimentary tract into that of the respiratory. Ridgway (1986) cited in Huggenberger et al. (2019) suggested that the lungs may serve some function as an oxygen storage organ at the very least during shallow water swimming (Huggenberger et al., 2019: 101). During the descent of deep dives, the lungs compress and the air is pushed into the upper divisions of the respiratory tract where the pressure aids in sound emission through the melon (Huggenberger et al., 2019).

The cetacean nasal passage is paired and, within the respiratory system of the Odontoceti - of which the harbour porpoise is a member - this passage fuses and terminates at the crescent shaped blowhole on the dorsal plane. Air is admitted into the respiratory tract through the voluntary opening and closing of the nasal plugs which project outward anteriorly into the lumen of the nasal passages and these airways remain closed underwater. The larynx then connects to the lungs via the trachea, which is short and has a relatively large diameter to enable a large volume of oxygen to flow quickly to and through the respiratory tract. Odontoceti have a horizontal trachea and the larynx is bent at a right angle - an anatomy called the goosebeak - to allow for respiratory flow between the blowhole at the top of the head and the lungs.

Whereas the human trachea is formed of cartilaginous rings connected by the trachealis muscles, the Odontoceti tracheal rings are connected with connective tissue and the trachealis muscles are not present. The tracheal rings of Odontoceti are fully circular and irregularly anastomose with one another; this is significant in post diving reinflation. The trachea ends at the main bronchi with one bronchus entering each lobe of the lungs. These main bronchi separate further into the lobar bronchi, then the segmental bronchi, and finally the bronchioles, with thinner and thinner cartilage as they progress. This is much the same as within the human respiratory tract, however the bronchial tree of the Odontoceti possesses myoelastic sphincters in the submucosa of the bronchioles which shut the respiratory bronchioles out and prevent the reflux of air into the alveoli. The function of these sphincters are not completely understood, although the relationship between air pressure in the upper respiratory tract and sound emission is clear (Huggenberger et al., 2019).

Topographically, the heart of an Odontoceti is located more postally than in humans, laying flat on the sternum; it is dorsal (rather than latero-dorsal) to the lungs, representing a difference in the spatial relationship between the heart and lungs than that of land mammals. The heart has four chambers - these are the right and left ventricles, and the right and left atrium. The basic anatomy of the heart is remarkably similar in appearance to that of terrestrial animals except it is larger and flatter due to the shape and pressure of the thorax.

The arterial blood supply in an Odontoceti begins with the ascending aorta that curves as the aortic arch - where it gives of the three main arterial branches - and then continues down as the thoracic and then abdominal aorta. The spinal cord is enveloped by a thick Retia Mirabilia - a complex arteriovenous structure in which a single artery branches into smaller blood vessels and reforms as a larger vessel as a direct continuation of the original artery and may function to decrease pressure - this is instead of the epidural fat in the vertebral canal of humans (Huggenberger et al., 2019). Houser et al (2010) confirmed that the main blood supply to the brain of a cetacean is from the spinal meningeal arteries (Houser et al, 2010) and Ridgway et al (2006) described an uni-hemispheric vasoconstriction, which enables cetaceans to partially shut down the blood supply to half of the brain, which is potentially significant during for prolonged breath hold dives (Ridgway et al., 1969 referenced in Huggenberger et al., 2019).

Multiple studies have demonstrated the benefits of 3D biomedical models when learning life science subjects (Keedy, 2011, Murakami, 2014, ten Brinke, 2014). There is a clear consensus that both digital and non-digital 3D models are favoured by students. Non-digital models are not just interactive - in lieu with their digital counterparts - but also provide haptic feedback. Recent advances in 3D printing mean that highly accurate models can be made on demand to incredibly detailed specifications. Azer (2016) reported that the implementation of 3D models within anatomy education makes learning easier and more enjoyable. Digital Models accessible through mobile devices can contribute making learning far more accessible and affordable to most (Eteokleous, 2019). This type of learning is referred as m-learning, the learning that happens with the use of a mobile phone and/or whilst the user is mobile, rather than the use of physical 3D models or even e-learning (Eteokleous, 2019)

Considering the wide range of digital resources available to support the learning of life sciences (Xiberta, 2018), there is, up to the knowledge of the authors, surprisingly few interactive, digital or 3D resources available for students of veterinary anatomy - and there is a particular lack within the field of marine mammal and cetacean anatomy, which could be used by volunteers. Effectively, most digital, interactive 3D educational resources and research have been aimed towards human anatomy education (Xiberta, 2018), marking a gap in available learning resources. 3D biomedical learning resources have proven a number of benefits over 2D resources; 3D resources enable a better understanding of 3D dynamics - for example orientation and location - then 2D images do (Azer, 2016). 3D models can also be interactive and used to display multiple angles of the same structure. The accurate production of 3D anatomical models can happen in a number of different ways: they can be produced as artistic interpretations through polygon mesh modelling and digital sculpting, or through the process of photogrammetry, or through segmenting and algorithmically triangulating voxels (indirect volume rendering) from medical image datasets - the most accurate ways of producing models.

Whilst relatively few, there are a small number of projects that demonstrate the benefits and uses of 3D anatomy within higher level cetacean anatomy education and research. For example, Kot (2020) described the benefits of using photogrammetry to create accurate 3D printed models of the skeleton of an Omura's whale that was stranded in Hong Kong. Thus, the creation of accurate mesh models and animations demonstrating the anatomy within the thoracic chamber of a commonly stranded marine mammal - the harbour porpoise - would provide an invaluable and much needed resource for volunteers on stranding schemes and students learning veterinary anatomy as well as providing proof of concept.

This research aims to provide a platform for teaching the basic anatomy of a cetacean and to determine how successful 3D technologies are as a distant learning teaching tool for teaching the anatomy of a dolphin in comparison to a more traditional approach. These will be achieved through achieving the following objectives:

1. Develop anatomically accurate 3D models of a cetacean. To ensure the anatomical accuracy of the models, these models will be developed from scan data and various anatomical sources will be referred to throughout the process.
2. Create an intuitive interactive mobile app that engages and educates on the anatomy of a cetacean that will be deployed on android devices.

3. Investigate the application's usability and potential to raise awareness about cetaceans' anatomy.

2 Materials

Table 1 describes the software, hardware, and data sources used for the creation of the application and the purpose they were used for as well as the company that the resource is produced by.

Table 1 - list of software, hardware, and data sources used for the creation of the app

Software	**Purpose**	**Produced by**
3D Slicer	A medical image informations programme used for filtering, data segmentation, and volumetric visualisation. 3d Sliver also has an extensive database of medical images, CTA Cardio dataset was obtained through this software.	Slicer 3D https://www.slicer.org/
MITK	A medical image informatics programme used for filtering, data segmentation, and volumetric visualisation. The lungs and heart models were segmented using this programme.	MITK https://www.mitk.org/wiki/The_Medical_Imaging_Interaction_Toolkit_(MITK)
Maya	A 3D modelling software that was used for retopologising, UV mapping, adjusting, texturing and animating the 3D models	Autodesk, Inc. https://www.autodesk.co.uk/products/Maya/overview

Table 1 - list of software, hardware, and data sources used for the creation of the app		
Mudbox	A 3D sculpting and texturing software that was used for sculpting and texturing the 3D models.	Autodesk, Inc. https://www.autodesk.co.uk/products/mudbox/overview
Unity	Used for developing the app and all interactions.	Unity Technologies https://unity3d.com/unity
Visual Studio	Used for developing C# code for interactions and more complicated elements of the app.	Microsoft Corporation https://visualstudio.microsoft.com/
Photoshop 2021	Used for creating and editing textures and artwork.	Adobe Systems, Inc. https://www.adobe.com/uk/
Illustrator 2021	Used for creating 2D content including UI buttons and logos.	Adobe Systems, Inc. https://www.adobe.com/uk/

Table 1 - list of software, hardware, and data sources used for the creation of the app		
Premiere Pro 2021	Used for assembling basic animations	Adobe Systems, Inc. https://www.adobe.com/uk/
After Effects 2021	Used for assembling and adding animated graphics to animations.	Adobe Systems, Inc. https://www.adobe.com/uk/
Hardware	**Purpose**	**Produced by**
MacBook Pro (Retina, 13-inch, Early 2015)	Laptop used for design and development.	Apple
Gaomon S260 oSU 6.5 x 4 inch Graphics Tablet	Drawing tablet used for texturing and digital sculpting in Mudbox and Maya, and for creating illustrations and 2D artwork in Illustrator and Photoshop.	Gaomon

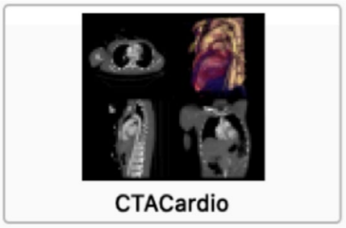
Table 1 - list of software, hardware, and data sources used for the creation of the app		
Samsung Galaxy M12 SAMSUNG	Mobile phone used to test the developed application	Samsung
Data	**Purpose**	**Produced by**
CTACardio  	Example dataset from which the human lungs and heart were segmented	Slicer 3D https://www.slicer.org/
CT of Harbour Porpoise 	Dataset from which the skeleton, lungs and trachea were segmented	Diagnostic Imaging, Faculty of Veterinary Medicine, Utrecht University, The Netherlands
MED302_c.JPG 	File used to texture the skeleton	Dosch Design, 2017 Courtesy of Mike Marriot
MED300_I.JPG 	File used to texture the skeleton	Dosch Design, 2017 Courtesy of Mike Marriot

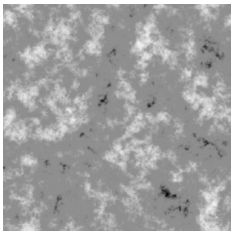
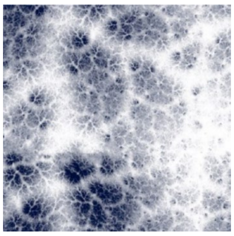
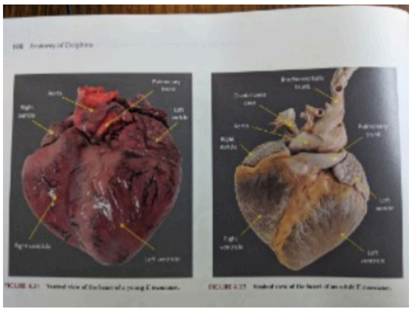
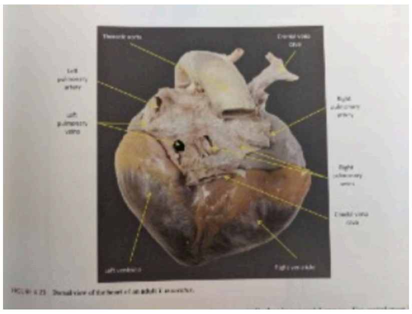
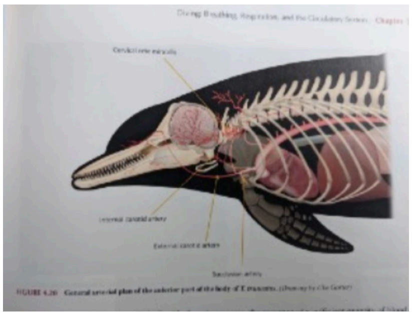
Table 1 - list of software, hardware, and data sources used for the creation of the app		
MED441_B.JPG 	File layered and used as a bump map on the skeleton model.	Dosch Design, 2017 Courtesy of Mike Marriot
MED301_B.JPG 	Files layered and used as a bump map on the skeleton model.	Dosch Design, 2017 Courtesy of Mike Marriot
Lung_Texture_By_Pauline_Moss 	File used as a bump map on the lung model.	Moss, P. Accessed May 2021
Ventral view of the heart of an adult T. Truncatus Ventral view of the heart of a young T. Truncatus 	Images used as a reference for ensuring the heart model was anatomically accurate to the heart of a harbour porpoise. Whilst the images are of a bottlenose dolphin, they are similar enough to be used for validation.	Cozzi et al, 2017

Table 1 - list of software, hardware, and data sources used for the creation of the app		
Dorsal view of the heart of an adult T. Truncatus 	Images used as a reference for ensuring the heart model was anatomically accurate to the heart of a harbour porpoise.	Cozzi et al, 2017
General arterial plan of the arterial part of the body of a T. Truncatus 	Image used as reference for ensuring the heart models spatial location and relationship to the lungs and Skelton models was anatomically accurate to the heart of a harbour porpoise.	Cozzi et al, 2017

3 Methods

The idea of creating the app came as a suggestion to create 3D interactive models that demonstrate the anatomy of a cetacean. Research suggested that the most effective result would be to focus on the thoracic anatomy of a harbour porpoise as it is a complicated area of anatomy in the most commonly stranded marine mammal on Scottish shores. The section of the cardiopulmonary system was also chosen because the development of the app was a proof of concept and this visualisation was achievable with the time and resources available. The resource aimed to be a complimentary and preliminary resource that would provide stranding volunteers anatomical data at the point of need.

Fig 1 - Design and development workflow

Storyboarding (Fig 2) is the preliminary stage in content creation and aided in planning the design and development of the app. The app was designed to include a menu scene, one main interaction scene, and two sub scenes with more detailed information on the lung and heart. A moodboard (Fig 3) was also created to develop the required aesthetic of the app and 3D models. It was decided to create realistic looking organs on a neutral colour scheme.

Fig 2 - Storyboard

Fig 3 - Moodboard

3.2 Development of 3D Content

The preliminary stage in 3D content creation is segmentation, creating Indirect Volume Renderings (IDVRs) from medical imaging datasets and saving these as .stl files, a common 3D media model file format. The image series from the CT scans were imported into 3D Slicer to be filtered and then were exported and reimported into MITK for segmentation. A mixture of manual and automatic segmentation techniques were used to ensure the most accurate models possible could be exported into the app. The dataset of the the Harbour Porpoise - provided by Diagnostic Imaging, Faculty of Veterinary Medicine, Utrecht University, The Netherlands - was used to create segmentation models of the lung, trachea and bronchial tree, skeleton, and skin of the harbour porpoise. The heart was developed from a segmentation model of a human heart, developed from a CTA Cardio dataset. A UL threshold was used to automatically select the relevant pixels on each dataset and following automatically selecting approximate values, the data was gone through on a slice by slice basis to neaten up the segmentation models.

Fig 4 - Process of segmenting the skeleton model

Lungs have very similar density throughout that is very different (much lighter in density so much darker in colour) than the surrounding anatomies. This normally makes them very easy to segment using only an automatic segmentation, however the dolphin lungs on the CT were out of habit and so were collapsed in some places and not one texture the whole way through as with human CT. This made the segmentation process much more difficult than anticipated.

Fig 5 - Final lung segmentation model

The skeleton model was the most difficult perform for a number of reasons. Bone density varies a lot within the skeleton and the cartilage that sits within the bone is far less dense and of similar density to the muscle and surrounding tissues so the data needed to be gone through on a slice by slice basis to get the most accurate and useful model possible as the original automatic segmentation was not accurate. A significant amount of manual retouching was needed to create a more accurate segmentation. For a more effective process, a polygon mesh was created and this was viewed with the cross hair showing so that the exact points where the model was being built could be located quickly and corrected in the correct plane.

Fig 6 - Final skeleton segmentation model

The development of the heart was also complicated as it was developed from human data rather than cetacean. Whilst the cardiac anatomies of cetaceans and humans are similar, they are not identical and do have marked differences. The heart is surrounded by pericardium and fat and so selecting pixels only relevant to the heart in 3DSlicer was complicated despite a number of variations in dataset filtering attempted.

Fig 7 - Final heart segmentation model (from human CTA data)

The skin was an incredibly simple segmentation as all data that was not the surrounding atmosphere or the CT bed could be selected and so a very wide UL threshold could be used and very little manual work was needed to tighten this model. It was created over two scans as the tail and body of the harbour porpoise existed in two separate files and these had to be joined in Maya during the retopology process.

Fig 8 - Final segmentation model of the skin of the harbour porpoise

Following segmentation, the models created from scan data using MITK had to be retopologised as they had a very high poly count - making them completely for use within mobile applications and very difficult to texture or animate effectively. The retopology of the skeleton was the most complicated as it was large and contained a lot of different angles. A rough retopology with very basic cube shapes was originally created and this was later refined to allow for more detail. This multi-layer retopology process also ensured that an efficient UV map could be created from the data.

Fig 9 - Before and after retopologising the lungs in Autodesk Maya

Fig 10 - process of creating a very rough and low poly topology on the skeleton model to allow for a more effective UV mapping process

Following retopology some artistic license was allowed through some further digital sculpting. For example, the ribs were thinned out slightly so that a more elegant look was achieved. Of course, as the heart was developed from human data, a lot of effort was put into the sculpting to ensure that it was accurate to the heart of a harbour porpoise. Changes included how the vessels twisted around each other and adding some further vessels down the sides of the aorta to hint at the retia mirabilia.

Fig 11 - Process of sculpting the lung models so that the ribs are correctly laid on top, the second ribs on the right is a good example of the models sharing the same space and so merging which is not anatomically correct.

Fig 12 - Process of using image planes to correct the heart model segmented from human CTA data to be more in line with the thoracic anatomies of a harbour porpoise.

Texturing was the next stage in 3D content creation. Planar based UV maps were created using the automatic feature inbuilt in Maya and this was used to work out where the UV set edges should be. This was tested using a checkerboard texture to ensure any texture would be placed evenly and allowing for an easier time creating textures.

Fig 13 - UV maps of the lung model with a checkerboard image applied to demonstrate where the UV seams are and that the seams appear almost seamless.

Textures were mainly made using the digital sculpting and painting programme Mudbox, although some textures were used from external sources for the lungs and skeleton models. The skin and heart model textures used colours from images taken by the author at a necropsy of a stranded harbour porpoise at the University of Glasgow Veterinary School, July 2021. These textures were developed through layering inbuilt skin filters with some further details added. Normal maps and displacement maps were also exported from Mudbox to aide in adding further minor details to the models.

Fig 14 - Texture map of the real heart model

Fig 14 - Displacement map of the heart model (used on both the false colour and real heart model)

Fig 15 - Normal map of the heart model (used on both the false colour and real heart model)

A secondary texture was developed for the heart model only, this was a false colour texture where bright textures were traced over the boundaries of the heart anatomies to better communicate spatial relationship.

3.3 Final Models

Fig 1 - Final lung and trachea models

Fig 14 - Final heart model with real texture

Fig 15 - Final heart model with false colour texture

Fig 16 - Final skin and skeleton models

3.4 Animations

Animation was the final stage in 3D content creation.

The lungs had two animations. Alveoli were created using MASH networks in Maya, they were then animated using transforms, to communicate the opening and closing of the myoelastic sphincters present at the end of the bronchial tree in a harbour porpoise. A sphere was animated to shrink and expand to simulate the alveoli filling with air and contracting and distributed along an organically shaped cylinder. The sphincters were animated through shrinking a couple of edge loops near the border of where the alveoli begin.

The body of the lungs was also animated using a blend shapes animation to simulate the expansion and contraction that would happen with breathing. The model was duplicated and then sculpted to appear bloated. The animation was baked into the model so that the animation could be viewed within the app from all angles.

These two animations were imported in After Effects as JPEG image sequences. The alveoli animation was masked within a circle and expanded out to fill the screen. This transition was to imply that the animation was zoomed in at this particular region of the bronchial tree. Further graphics were added to add further information about the relevant anatomies shown in the animations.

Fig 17 - alveoli expansion animation still

The heart was animated using a blend shape animation to simulate a heart beat and better communicate blood flow direction. The heartbeat was rendered at two different speeds to allow for comparison between the submerged and at surface heartbeat patterns. A simple blood cell model was created and animated using MASH networks as it is a recognisable element of blood that is easy to model. Labels of each cardiac vessel were carved into the models using boolean functions to provide 3D information about the structures the user was viewing. Table 2 describes the timings of the auricle contraction and ventricle contractions to ensure the beating was timed correctly with the two rates of heartbeat where the little cube represents the blend at 0 and the big cube represents the blend deformer at 1.

Table 2 - describing the heartbeat animation timings.

Auricles				
Ventricles				

Submerged (40 BPM)	9.375	18.75	28.125	37.5
Surface (105BPM)	3.57125	7.1424	10.7136	14.285

A final video was made using the volumetric scan data of the harbour porpoise from Diagnostic Imaging, Faculty of Veterinary medicine, Utrecht University, The Netherlands. The data was played through and the lungs and bronchial tree were highlighted using trim paths in Adobe After Effects.

3.4 Application Development

2D content - namely the logos and UI buttons - were created using Adobe Illustrator. The UI were created in two contrasting colours so they would be usable irregardless of the background colours of that particular scene. For the navigation buttons, high quality Arnold renders were created and masked into the same rounded rectangle as is used for the interaction button. This was understood to be the clearest way to communicate the actions that these buttons performed.

Fig 18 - navigation buttons made by masking renders onto a square shape

The UI was planned in detail using Adobe InDesign (fig 18). This map provided a reference point for the researcher to follow in the development of the application. The app was developed in Unity, originally solely as the UI flow using basic buttons to ensure that the user journey between scenes was smooth and that the placement of the UI content was effective.

Fig 19 - plan of UI

All interactions were created using Unity and C# code. A alpha application was run, using cube in space of the anatomy models to ensure functionality was correct before inputting the models. A beta was then developed and revealed a number of issues to be solved. A number of test builds were completed and run to debug in order to ensure as few bugs as possible were present in the final result.

4 Results

The Digital Dolphin app presents the user with very simple UI that is designed to allow the user to easily navigate through the various functions available. Fig 20 demonstrates the user flow in detail.

Fig 20 - user journey

The app opens with entrance animations displaying the authors own logo and the logo of T*he Digital Dolphin*, designed in Adobe Illustrator. This animation is used also as a scene transition to allow a smooth flow as the user progresses through the app.

The start scene utilises very simple UI to guide the user towards the main anatomy scene. There is an additional UI button that utilises traditional symbols to enable the user to learn more about the author, app, and relevant credits. A two way exit dialog allows the user to leave the app only on purpose.

Fig 21 - Start scene

The anatomy scene is the first scene that the user must view and hosts each of the main models central on scene with the skin model initially hidden. A darkened skin button indicates the purpose of the lower UI panel. The user has the option to toggle models on or off to view the anatomies below and create a scene that is useful for them to understand the spatial relationship of the thoracic structures. The user can rotate around the models using a tap and drag camera orbit functionality and the camera reset button allows the user to return to the original camera position. When the skeleton and skin models are turned off, the camera rotates around the lung model instead so that the user can better understand and see the spatial relationship here.

Fig 22 - Anatomy scene

From the main anatomy scene, the user can then progress to the lung or the heart scene. This is indicated through the larger, outlined buttons. A panel opens upon pressing one of the scene progression buttons to ensure that the user does want to progress further into the app. A semi transparent background panel partially obscures the rest of the scene so the user is better able to focus on the transition panel information.

The lung anatomy scenes places the lung model central on scene. The user has options to turn the lung model on and off to view the bronchial tree below and better understand this spatial relationship. There are options to play lung breathing animations, or to reveal information panels when pressing on points of interest on the lung or trachea with further animations available within. There is also a sequence of scan data to enable the user to understand how these structures appear on CT.

Fig 23 - Lung scene

Fig 24 - Lung interactions

The heart anatomy scene places the heart model central on scene with UI panels down the side. The action buttons are on the left and the navigation buttons on the right hand of the screen. The user has options to view a heart beat animation at the average surface speed of 40BPM, or to change the texture of the heart model to better understand the boundaries between vessels and compartments. There are 5 main points of interest with animations and images of coronary vessels and 4 minor interest points that labels the ventricles and auricles.

Fig 25 - Heart scene

Fig 26 - Heart interactions

5 Evaluation

In order to evaluate the usability of the app and the anatomical accuracy of the models, preliminary pilot testing was undertaken to get a basic idea of the user experience generated by the app.

5.2 Participants

Three, highly skilled cetacean anatomists were recruited through the director of SMASS, Dr Andrew Brownlow. Cetacean anatomy experts were chosen as the target testing group as they would be able to answer both whether the models were anatomically accurate as well as give feedback on the usability of the app as they would have both worked with and aided in the training of stranding volunteers.

5.3 Procedure

The participants were directly emailed with a Participant Information Sheet which contained a brief description of the project aims and links to the following: the consent form which had questions to ensure proper consent was given, the download link for the app itself, and the post-app questionnaire which had a number of questions on the anatomical accuracy and the usability of the app. The Participant Information Sheet asked the participant to first complete the consent form, download and install the app and try to use it, then complete the accuracy and usability questionnaire.

Two questionnaires were built using google forms that could be accessed digitally and remotely by the study participants. Both questionnaires adopted a 5 point Likert scale with the value “1” to indicate that the participant strongly agreed, and the value “5" to indicate that the participant strongly disagreed. This was later inverted to complete the evaluation as “5” is usually associated to a positive response. The two questionnaires were in line with the aims of the research.

The first questionnaire was developed to gain awareness on the anatomical accuracy of the models. This asked questions on the anatomical accuracy, spatial relationship, and for any additional comments that the participant may have that would help the researcher better understand their stance on the anatomical accuracy of the app.

The second questionnaire was to gain understanding on the usability, user experience, and effectiveness of the app that utilised the highly standardised System Usability Scale (SUS) (Tullis and Stetson, 2004). The SUS consists of a ten-statement questionnaire which is very easy to use and wields accurate result even with small sample sizes, enhanced with two additional questions. The first additional questions was about whether the participant would recommend the app to a colleague or friend. The second additional question was an open-ended question to capture any further thoughts or recommendations from the participant.

5.4 Data Analysis

The data on the anatomical accuracy was analysed first by assessing how well the models were received by the participants. It was easy to determine how accurate the models were viewed as the questionnaire used the Likert scale.

The SUS test scores were calculated and this number was used to assess the usability of the app and the user experience.

5.5 Ethical Approval

Ethical approval was granted by the Glasgow School of Art.

5.6 Results

The first three questions aims to prove further understanding of the anatomical accuracy of the models in the app. Two quantitive questions and one qualitative question were posed to the participants. These were on the anatomical accuracy of the models and on the spatial relationship of the models. Two of the participants scored the models as highly anatomically accurate and with accurate spatial relationship and one participant scored the models as low on anatomical accuracy and with low accuracy spatial relationship. The mean average of responses is 3.33 which is relatively accurate.

Two of the participants scored the models as highly anatomically accurate (fig 31) with accurate spatial relationship (fig 32). The final participant scored the models as low on anatomical accuracy with low spatial relationship accuracy. This was less positive feedback than expected and suggests that the models can be seen as anatomically accurate but need some refining. The participant that scored low, stated that the models were incomplete, stating that the models could not be seen as accurate as there is only one model with only partial organs present. As such, it is indicative that further 3D model creation would be necessary to fully engage and understand the anatomy. Another participant called for the rate and aortic vessels to be incorporated into the cardiac vasculature. Again implying that further 3D model creation is necessary in order to communicate these anatomies correctly.

Fig 31 - graph illustrating the individual responses to the anatomical accuracy

Fig 32 - graph illustrating the individual responses to spatial accuracy

The second questionnaire, the SUS, indicated a usability score of 79.2 when 68 is seen as average (fig 33). A score of more than 68, suggests that the app may function with a usability of above average. However, it is important to note that the SUS encourages a participant pool of no less than 5, so this data can merely be suggestive and cannot be seen as a definitive result.

Fig 33 - graph of the individual SUS scores

On a final note, one participant rated the usability of the app as slightly lower and this is the same that said that the models were less accurate, implying that this participant did not have a good experience, especially compared to the other participants. In the second long answer question, this participant said that the app would be "possibly useful for students but less useful for experienced pathologists or anatomist", suggesting that perhaps they felt the app was below their skillset and so not worth their time exploring. In future testing, it would be interesting to see if there is any further demographic cause for why this participant did not enjoy the app as much as the other participants.

The results of testing were mainly positive and revealed that further development and refining of the 3D models would need to be undertaken, with more models added to better increase the spatial relationship accuracy. The pilot testing was very supportive of further work being completed. When asked if they would recommend this app to a friend or colleague, all participants responded positively with one stating that they "would certainly use it to illustrate anatomy to the volunteers who assist me with post mortem examinations" demonstrating that the app has the potential to be a useful app for volunteers on stranding schemes learning the basic anatomy of cetaceans.

6 Discussion

Existing literature clearly shows a lack of digital and 3D resources available to those wishing to explore and learn the basic anatomy and pathology of cetaceans. As necropsies of stranded marine mammals is increasingly facilitated by networks of volunteers over experienced pathologists of anatomists, this lack of resource is becoming an ever crucial gap to fill. Multiple studies have demonstrated the benefits of 3D biomedical models when learning life science subjects (Keedy (2011), Murakami (2014), ten Brinke (2014) and there is a clear consensus that both digital and non-digital 3D models are favoured by students as they are a more enjoyable learning experience, even with no apparent improvement in test scores (Azer; 2016). The results of this research favoured the development of 3D models to enable a better understanding of the spatial relationship of the anatomies of a cetacean.

The research focused on the thoracic cavity of the harbour porpoise as these are the more complicated and interesting anatomies with numerous pathology to consider within the process of necropsy. The app ran with no bugs, although the camera orbit could have been implemented to provide smoother orientation around the models. The app was well received by participants. Eteokleous (2019) suggested that learning that the advancement of m-learning over the use of physical 3D models or e-learning is a far more accessible means of accessing information. In that all of the testing was conducted fully remotely in a very tight time allowance and was still able to receive meaningful responses, this research does agree with this statement.

Testing was only preliminary, but even this testing highlighted that the app did not display accurate enough 3D models and further time needed to be put into the heart model in particular. The anatomical accuracy of the models rated lower than expected. The data from the qualitative question suggests that one participant found the models incomplete as they said "*there is only one model with only partial organs present so it's not particularly accurate as it is*." This is potentially as a result of the flipper bones removed and that only the main anatomies of the thoracic cavity were models which is perhaps not enough models to be able to tell whether the partial relationship is accurate. Another participant, whilst scoring the models as anatomically accurate with a score of 4 and spatially accurate with a score of 4 called for the rete and aortic vessels to be incorporated into the cardiac vasculature of the heart model. In future developments of this work, a further test may be advised to research which of the models are less accurate with the five point Likert scale used for each of the models individually. The app was mainly proof of concept and full implementation would be able to address these concerns relating to the lack of completion of the 3D models.

That the heart is to be seen as incomplete to a severe enough degree as to be viewed as not anatomically accurate is is not surprising as the heart model was developed using human CT data due to difficulties sourcing a relevant dataset of a cetacean heart. After segmentation the heart from human CTA Cardio data, the model was sculpted and further details amended to correct the anatomy and make it more anatomically accurate to the heart of a harbour porpoise. This was not done accurately enough or completely enough to be fully believable. This could also be what the other participant was referring to regarding incomplete models, however this theory is inconclusive without further testing. It is crucial to draw attention to the fact that the heart model was viewed as the least accurate according to the pilot testing. This is an important distinction as polygonal and mesh modelling methods are freehand methods that lend themselves to artistic license, much like with 2D anatomical illustrations and images that are the prevalent form of communication within atlases and learning resources (Azer, 2016). These models are less accurate than segmentation or photogrammetry produced models as they do not come from already existing precise anatomical information but rather from artistic interpretation. The flipper bones of the skeleton were also emitted due to time constraints and as they were not directly relevant to the thoracic anatomy. The lack of completion in these areas clearly had a detrimental effect on the quality of the final outcome.

With that said, the models incorporated, whilst not as anatomically accurate as segmentation models would have allowed, are still hugely effective at communicating the processes and structures of the thoracic anatomy and are more beneficial that 2D images would have been in that multiple viewpoints of each structure was offered and the user was able to view each model in relation to one another in a way a classical 2D image would not have allowed.

The SUS encourages a participant pool of no less than five; with a participant pool of 3, this data can only be suggestive of how the app really scores and the score achieved cannot be seen as a definitive result. These results are, nonetheless promising of a highly user friendly app. It is also worth bearing in mind that the boundary score of 80.3 is indicative of an app with excellent usability and with a current score of 79.2 and with some minor refinements, The Digital Dolphin app has the potential of achieving excellent in usability according to this scale.

The main limitation of the study was the time available to complete it. The research was completed in less than three months and, with more time, could have been far more developed. Certain functionality had to be revised to ensure that a working prototype could be tested and these revisions were felt most strongly in the strength of the testing completed and the overall completion of the 3D models. Demographic information was missing from testing, as well as a significant enough study pool to draw out meaningful evaluation. That said, the preliminary testing did highlight a number of promising ways that this research could be extended.

7 Conclusion

The Digital Dolphin highlighted a gap in the resources available for learning cetacean anatomy. The aim of the project was to create anatomically accurate, interactive, mobile-based 3D models that would help volunteers on stranding schemes understand better the structures they regularly need to sample.

There are a variety of ways that this research could be developed as there is so little currently available. Testing implied that developments of the heart model is a crucial next step before expanding the app to include the rest of the internal viscera. The app could also describe in detail the skeletal system and external factors relevant to stranded marine mammal necropsy, such as common skin lesions resultant from bycatch trauma or disease. The app is designed in such a way that further scenes could be easily incorporated. Using high contrast CT data to get better segmentations of the viscera would greatly expand the accuracy of further anatomical 3D models added.

The results suggest that 3D visualisation techniques are an effective means to engage and teach anatomy of cetaceans and it is clear that *The Digital Dolphin* app has the potential to become a complete concept that would be an invaluable asset to stranding programme volunteers learning the basic anatomy and pathology of marine mammals. Although, further testing would be needed to confirm the trend.

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