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SCIENTIFIC AND TECHNICAL

The devil is in the details: developing a modern methodology for detailed medical illustrations

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ABSTRACT

The Pernkopf Atlas has posed an ethical dilemma for the past 30 years. Although its illustrations are of an indisputably high quality, its unethical origins yield questions with its use. This study aimed to identify successful methods for creating equal if not higher quality anatomical visualisations through an analysis and comparison of past and present medical illustrator's techniques. Pernkopf's illustrations were not used as an anatomical reference to ensure the new visuals were ethical; instead other existing visuals and written sources were compiled and reviewed to create an original 3D model of the posterior cervical triangle using ZBrush 2020. Some visualisation techniques used by Pernkopf were used as a part of this project (i.e. rendering in partial colour) this technique is not unique to Pernkopf and was also used by Henry Carter, the illustrator of Grey's anatomy. The survey was distributed to 78 participants with a strong anatomical or medical/biological art background. The reception to the new resource was positive; participants favoured it in terms of quality and ease of understanding. However, participants noted that the images in the survey were not the same resolution which may have skewed the results in favour of the new image. When rated for detail compared to the Pernkopf Atlas, the number of structures in the resource need to be increased before it can be ranked equally to the Pernkopf Atlas for detail. Participants did note that they may have selected differently depending on what was inferred by quality and detail in the survey.

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KEYWORDS
Medical illustration; head and neck anatomy; 2D versus 3D visuals; pernkopf atlas; comparative visualization; detail level in illustration

Literature review

Between 1930 and 1960 German doctor Eduard Pernkopf developed an anatomical atlas known as *Pernkopf, Atlas of Topographical and Applied Human Anatomy* (hereinafter referred to as the Pernkopf Atlas). In the 1990s, an investigation revealed that the atlas had utilised executed National Socialist political prisoners as a reference to create up to 50% of the drawings. The book was taken out of print in 1994, however, the book is still considered, by some, to '… be the best example of anatomical drawings in the world. It is richer in detail and more vivid in colour than any other' (Baker, 2019). Despite its origin, many medical professionals still reference it to complete complex operations. While the use of the Pernkopf Atlas is controversial, the need for the atlas's continued use indicates an inadequate availability of equally detailed resources in the 21st century. People now have the capacity to create higher quality visualisations, indicating the potential to create anatomical depictions surpassing the detail and accuracy of Pernkopf's illustrations.

Comparison of past medical illustrators

As a part of this study three medical illustrator's works were compared to a newly developed visual: Henry Carter, the illustrator of Grey's Anatomy; Eduard Pernkopf's illustrators; and Frank Netter. Henry Carter was the first to comprehensively document human anatomy. Using pen and ink, Carter drew from direct observation in the dissection room. Prints of his work often add colourization to the nerves and vessels however, due to the limitations of colour printing, Carter's illustrations were created as black and white line drawings. Later improvements in colour printing allowed a more comprehensive record of human anatomy to be created by Netter and Pernkopf (Netter & Friedlaender, 2014).

Frank Netter and the illustrators employed by Eduard Pernkopf are classified as some of the most successful medical illustrators in history. The methods, circumstances, and environment in which their

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work occurred can help clarify which aspects of their work were successful. Netter and Pernkopf had ready access to cadavers for reference (Baker, 2019; Netter & Friedlaender, 2014). Additionally, both men took advantage of colour's capacity to bring the anatomy to life. While Netter's Atlas is considered by some to be less detailed than Pernkopf's, it is the closest comparison to the Pernkopf Atlas due to its detail and comprehensive content. When viewing the Pernkopf Atlas at the National Library of Scotland in February 2020, the author noted that the illustrations implement a style that uses selective colour and monotone rendering. Relevant structures are emphasised through the use of colour while the less relevant anatomical structures fall into the background. This stands in contrast to Netter who produced full colour illustrations (refer to (Berger, 2020) for illustration comparison). Another critical practice in medical illustration is how medical illustrators select the anatomical structures to include in their visualisations (Svakhine, Ebert, & Stredney, 2005, p. 31). The continued perception of Pernkopf's success relative to Netter's indicates that Pernkopf's selective process may have been more effective, especially in specific anatomical regions.

As mentioned in the literary review, up to 50% of the cadaveric references used by Pernkopf could have been victims of the National Socialist (NS) during the Nazi occupation of Vienna (Baker, 2019). Dr. Sabine Hildebrandt, an expert on the Pernkopf Atlas, discusses this and Pernkopf's NS associations in her 2006 paper, How the Pernkopf Controversy Facilitated a Historical and Ethical Analysis of the Anatomical Sciences in Austria and Germany. She notes that Pernkopf was a member and supporter of the NS before and during their occupation of Vienna (p. 92). Additionally, Hildebrandt provides a breakdown of how it is calculated that up to 50% of the illustrations could have been created from referencing prisoners executed by the NS:

> About half of the original 791 illustrations in the anatomical atlas were not created during the Nazi years as they either predate 1937 or were produced after 1945. Forty-one plates were definitely signed with dates from the Nazi period and it is likely that at least some of the models came from the group of 1377 executed victims. (p. 95)

Alternatively, Netter's anatomical references would have been ethically sourced and he had no association with the NS. The legal differences between NS occupied Europe and the United States may have benefitted Pernkopf's work by making human references easier to acquire. As mentioned above, cadaveric references are an integral part of creating accurate medical illustrations.

Modern practices in medical illustration

From the early 2000s onward, the use of 3D digital models has revolutionised anatomy education. Since the introduction of 3D models into education, research has established some of the benefits of digital 3D resources. Twenty-eight prominent publications about the use of digital 3D models in the classroom were reviewed in the *Journal of Science Education and Technology*, '… the majority (74%) of studies indicate that the use of 3D is beneficial for many tasks in anatomical education, and that student perceptions are positive toward the technology' (Hackett & Proctor, 2016, p. 641).

One recorded benefit of the Pernkopf Atlas is its detailed neuroanatomical depictions (Baker, 2019). Neuroanatomy is often documented as one of the more difficult subjects to learn in anatomy. Three-hundred eighty-three students from a variety of medical and anatomical backgrounds were surveyed on their existing perceptions of neuroanatomy; 33.3% of students ranked 'appreciation of 3D relationships' as significantly important to their understanding (Javaid, Chakraborty, Cryan, Schellekens, & Toulouse, 2018, p. 87). Additionally, the questionnaire asked students to comment on the importance of different teaching methods; 3D reconstructional videos ranked sixth out of the 15 methods students could choose (Javaid et al., 2018, p. 89). The increased use of digital 3D models in education and medical practice, along with the positive reception of study participants, indicates that 3D visualisation plays an integral part of developing new visualisation techniques (Crafts et al., 2017; Kockro et al., 2015; Maniam et al., 2020).

Some researchers have experimented with computer generated 3D medical models. In a past study, researchers at Purdue University noted, 'The enormous amount of 3D data generated by modern scientific experiments, simulations, and scanners exacerbates the tasks of effectively exploring, analyzing, and communicating the essential information from these data sets' (Svakhine et al., 2005, p. 31). To compensate for the computer's inability to identify and emphasise relevant structures, researchers worked with a medical illustrator to better understand the selective process utilised by medical illustrators when working to convey specific meaning through their illustrations (Svakhine et al., 2005, p. 31). The complication faced by the team at Purdue emphasised the connection between effective visualisation and selective detail.

The posterior cervical triangle

This project focussed on creating a detailed and realistic depiction of the posterior cervical triangle. As a part of the project, the authors consulted Dr. Susan Mackinnon, a plastic and reconstructive surgery specialist at Washington University in St Louis, who has used the Pernkopf Atlas throughout her surgical career and contributed to the development of ethical procedures for using the book (Baker, 2019). She identified Pernkopf's illustration of the posterior cervical triangle as being one of the illustrations important to her practice *(S. Mackinnon, personal communication, April 18, 2020)*. Additionally, it should be noted that surgical injury during operations in this area is high, indicating a need for additional and more accurate visualisations of this area (Park et al., 2015).

Surgical complications

A 2007 study, states that injuries to the Spinal Accessory Nerve (SAN) result in from 3% to 10% of lymph node biopsies in the posterior cervical triangle. The high rate of injury raises alarm and has led to further studies seeking to make the procedure less dangerous (Boström & Dahlin, 2007). In the 2015 paper, *Surgical outcomes of 156 SAN injuries caused by lymph node biopsy procedures*, Park et al. noted that injury to the SAN is more common in Zone 1 (see Figure 1) of the posterior cervical triangle, partially attributing this to the high level of variation in the area (p. 520). To better understand how anatomical variation affects surgery in the area of the sternocleidomastoid (SCM), Surgeon Mr. Rod Mountain, an Ear Nose and Throat Surgeon at Ninewells Hospital in Dundee, was consulted. Mr. Mountain noted that the SAN is often depicted crossing horizontally across the posterior cervical triangle. However, more often it crosses obliquely at a 45 degree angle (R. Mountain, personal communication, May 27, 2020). For this project depiction, the SAN will be depicted in line with the observations of Mr. Mountain as closely as possible. Because of the high rate of surgical injury in this area, the posterior cervical triangle was chosen as the anatomical region for this study.

Methods

Given the timing of this study relative to the 2020 outbreak of COVID-19, access to cadavers for reference and dissection was not possible. While this may have compromised the integrity of the process, the increased documentation of anatomy over the past century helped to compensate for this deficit (see online materials for visual references).

Process work and initial file setup

To prepare for the creation of the 3D model, many 2D drawings were created (see Figure 2). The more refined sketches created during this part of the process were sent to Dr. Catherine Carr and Dr. Seaneen McDougall (anatomists at CAHID) and Mr. Mountain (ENT surgeon at Ninewells). They noted the great auricular nerve and phrenic nerve needed to be adjusted and that the phrenic nerve originates from C3 to C5 however it was originally depicted coming from C4 (C. Carr, personal communication, May 20, 2020; S. McDougall, personal communication, 20 May 2020). The sketch was also adjusted to clarify

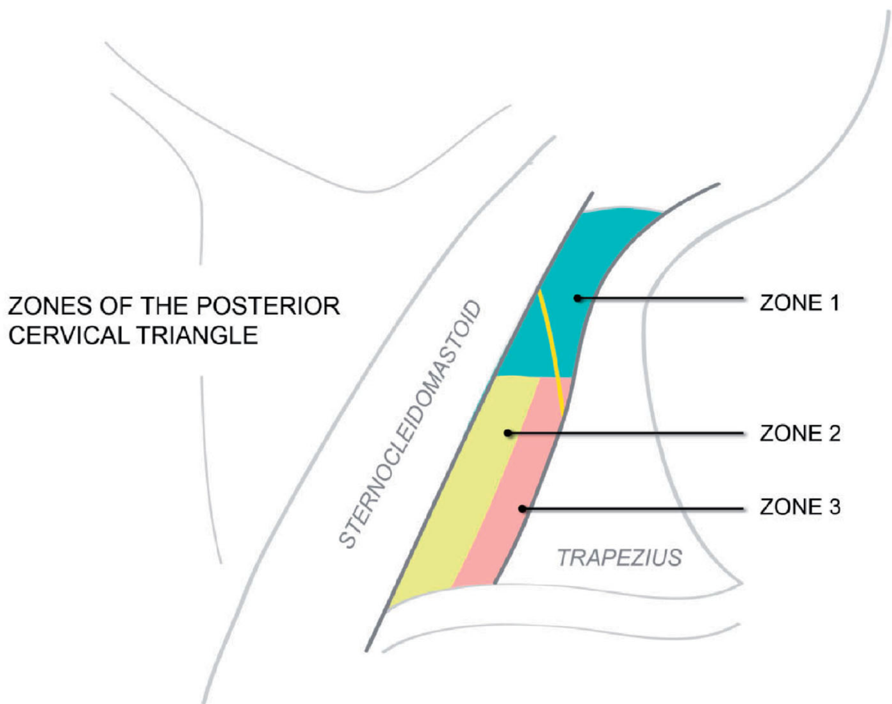


Figure 1. Three zones of the posterior cervical triangle.

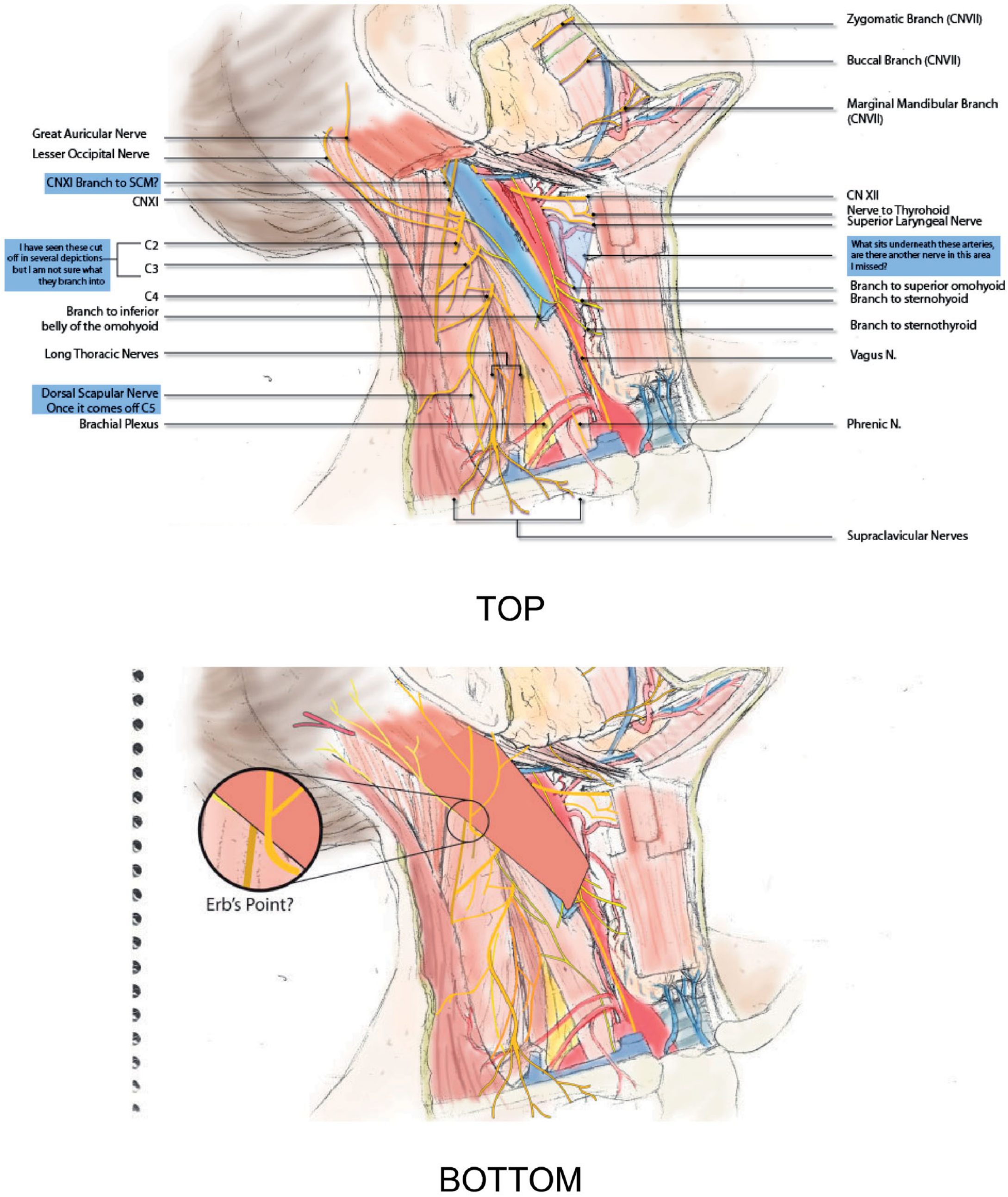


Figure 2. 2D Guideline image. Top: Blue highlights mark areas in question. Bottom: Process work after second round of revisions.

the location of the SAN relative to the great auricular nerve by adding a close up of Erb's Point. Erb's Point is the place where the SAN sits approximately 1mm above the great auricular nerve, which is a place of clinical relevance (R. Mountain, personal communication, 27 May 2020).

3D Modelling

ZBrush 2020, a 3D sculpting software, was used to create the model. Anonymous patient CT data of the scapula, clavicle, and part of the spine were imported into ZBrush as .OBJ files to use as origins and insertions while building the neck muscles. The female demo head that comes with ZBrush was used as the base for the head and face. To construct the muscles, cylinders were used to create the approximate shape of the given muscle and then merged and dynameshed (retopologized to convert mesh to a quad mesh). The model was built using the MatCap Red Wax (default) material before any colour was added (see Figure 3). Using Alpha 60 and the Standard Subtract Brush, the striations of the connective tissues and muscles were implemented An Alpha is a displacement map that allows the user to sculpt a specific pattern into the subtools in ZBrush. Alpha 08 and 23 were used in combination with the Standard Add Brush to add texture to the skin such as pores (see Figure 4). Once the sculpted structures were established in the MatCap Red Wax material, and the larynx and large vessel place holders were implemented, the materials were adjusted to either SkinShade4 or ToyPlastic depending on the necessary glossiness of the structure.

Building the vessels and the nerves

ZSpheres were used to build the vessels and the nerves after the muscles, glands, and thyroid were colourized. ZSpheres were chosen for building vessels and nerves because they allowed for the creation of thin long structures. Each sphere added creates a new connection between the previous spheres (see Figure 5). To make the ZSpheres an editable subtool, the Adaptive Skin Option was used. On the right side, the terminal ends of the cutaneous branches were added to the skinned cervical plexus. The Sternocleidomastoid transparency was adjusted using Display Properties > BPR Settings to adjust the muscle so the cutaneous nerve origins could be seen below the SCM (see Figure 6). Due to time limitations, the number of nerve and vessel branches included in the final 3D model was less than anticipated. This may have had inadvertent effects on the results of the survey, as many participants noted the new visual was easier to understand than Pernkopf's.

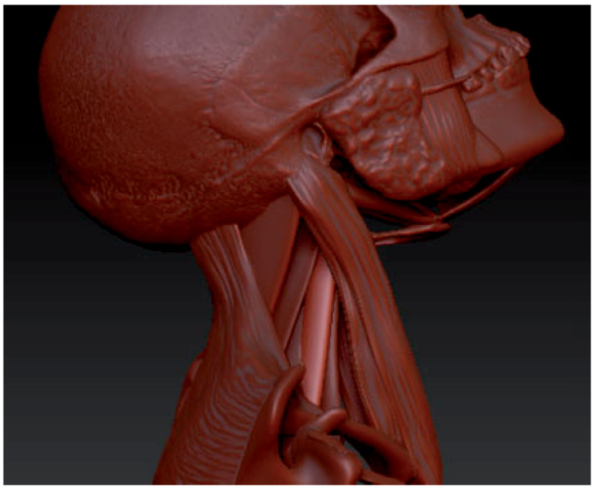


Figure 3. Cylinders morphed, scaled and sculpted into neck muscles shapes.

Polypaint and colourization

To colourize the structures, Polypaint and four Alphas were used to create the various textures and striations.

Muscle, bone, and additional structures colouration

Abase colour was applied to the various anatomical structures (subtools) and then the details were

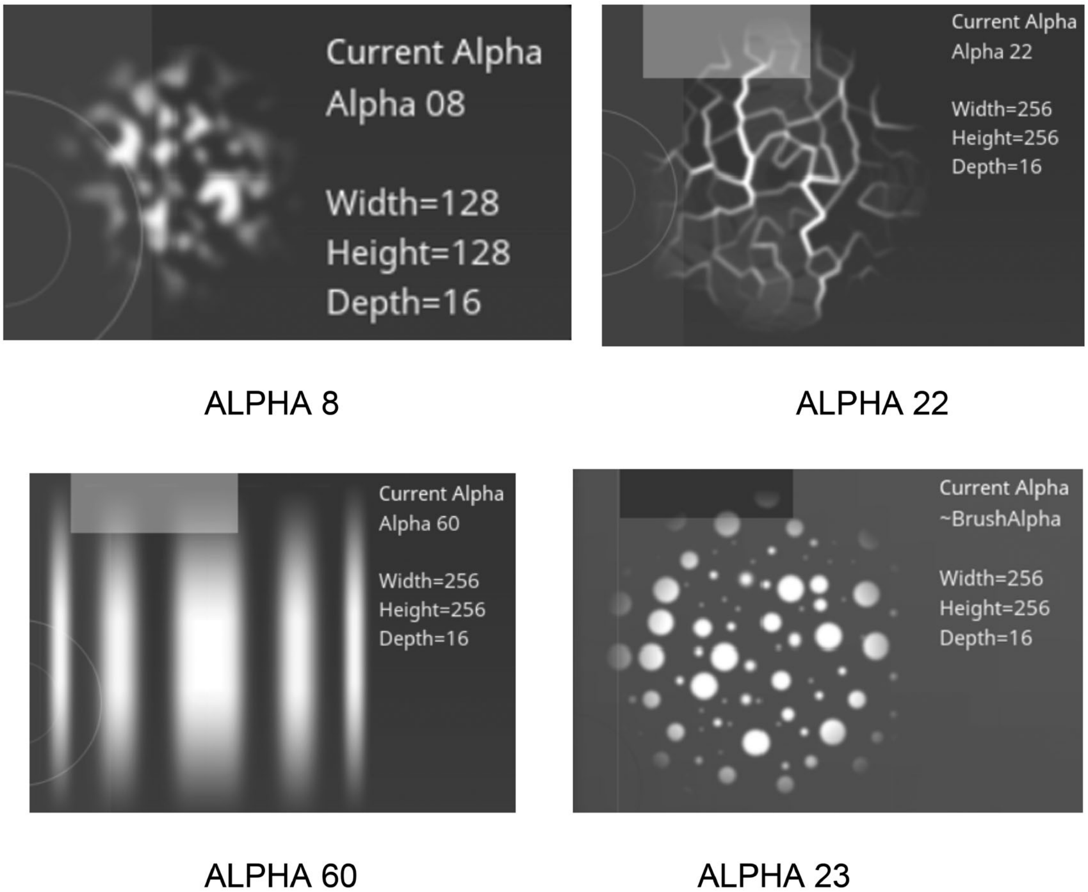


Figure 4. *Alphas used to create texture and colouration.*

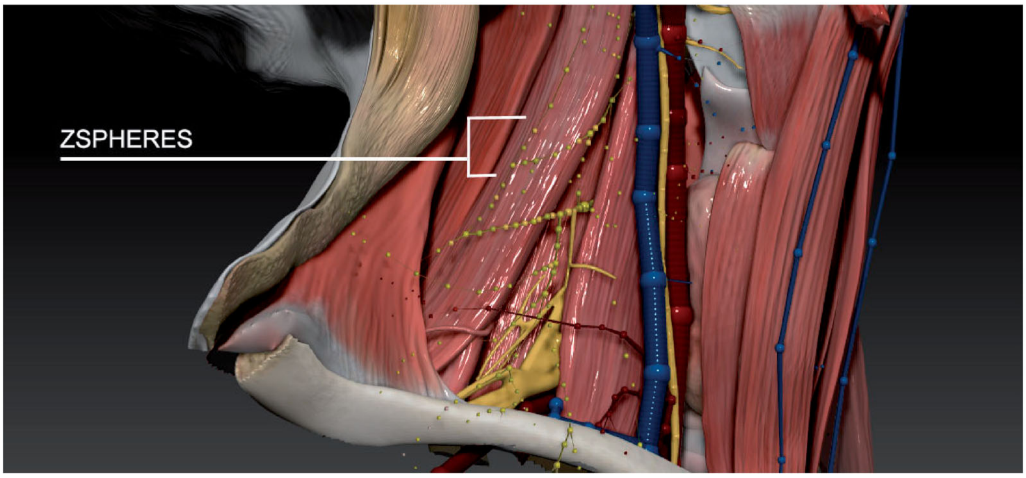


Figure 5. ZSpheres forming the nerves, veins, and arteries.

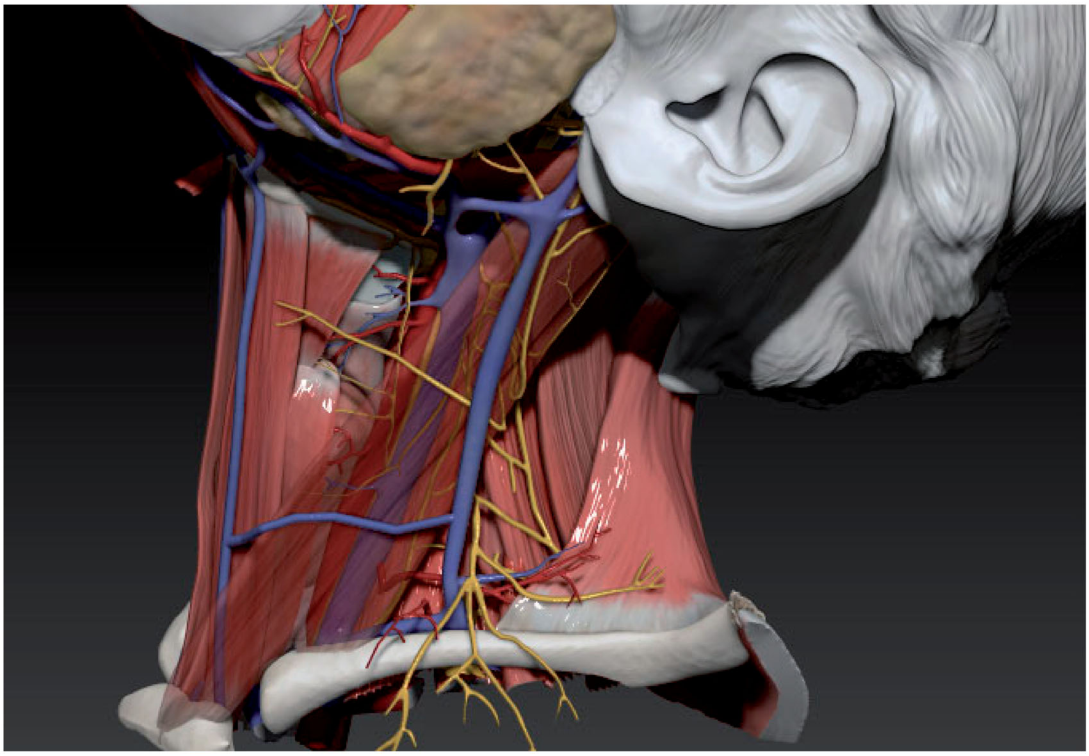


Figure 6. Transparent SCM on left side of model.

drawn on boldly using the Polypaint feature (see Figure 7). After the details were applied, more neutral colours such as white, light grey, and light yellow were applied to better blend the details with their surroundings. In areas with a high amount of small vasculature such as the glands and the larynx, Alpha 22, was used to apply a red and blue translucent tint. For the muscles themselves, Alpha 60 was used to apply the striations. The bones' colouration was implemented using Alpha 08 with alternating colours (see Figure 4).

Greyscale version

An alternative version of the model was also created in which the skin was portrayed in greyscale for the colour comparison section of the survey. The BrushTxtr Tool was used to paint on a sculpture-like texture (see Figure 8).

Anatomical and artistic feedback

The 3D model underwent two rounds of feedback. Dr. Carr and Dr. McDougall reviewed the 3D models' anatomy. The draftsmanship and artistic technique was reviewed by Dr. Caroline Erolin and changes were made accordingly (Figure 9).

Survey design and thematic analysis

The University of Dundee, Centre for Anatomy and Human Identification, ethics committee approved

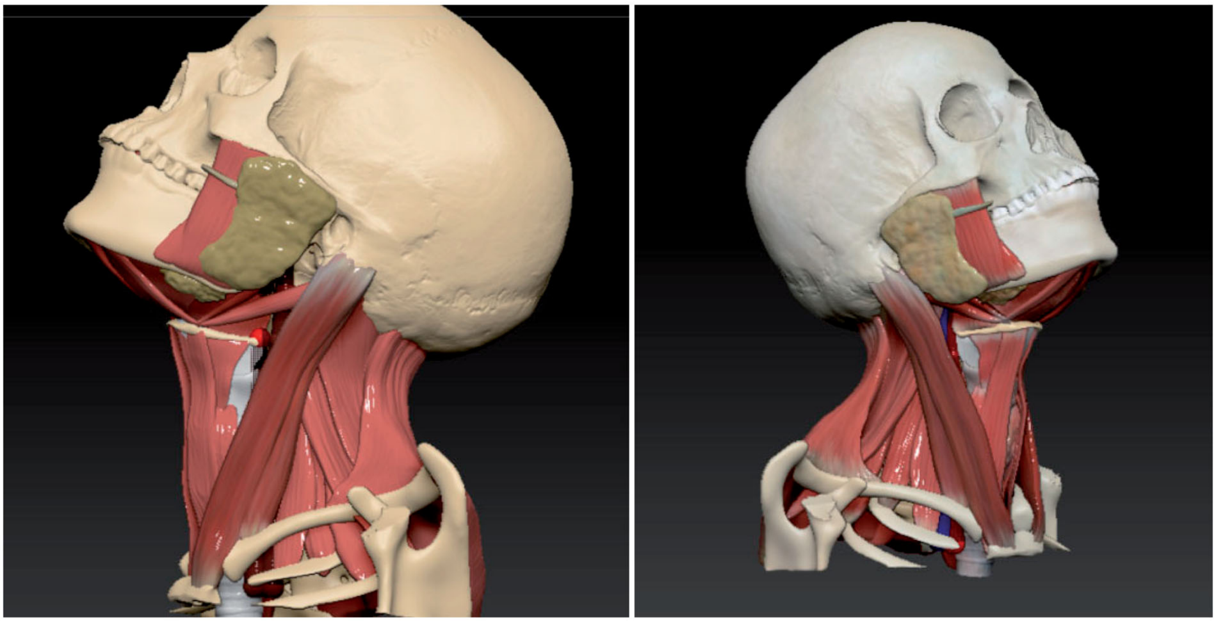


Figure 7. Muscle and skull colouration in progress.

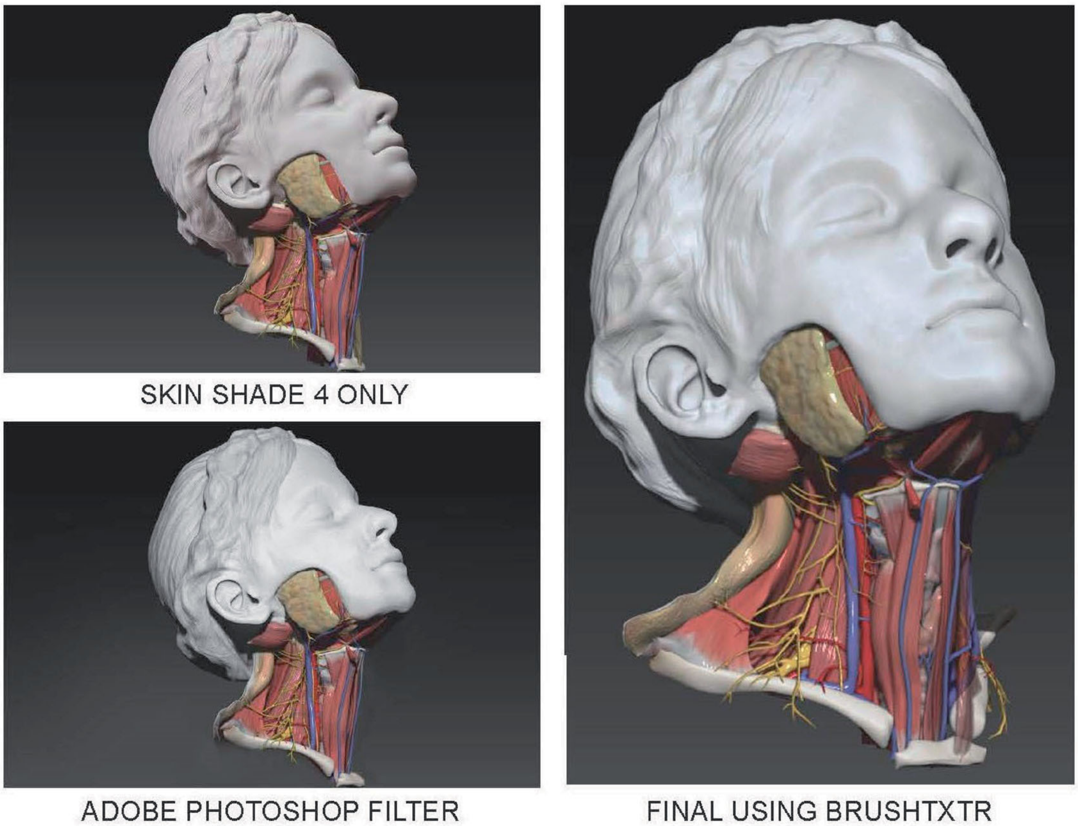


Figure 8. Progression of greyscale variation of model.

survey number UOD_SSEREC_CAHID_MSc_2020_005. The licence to survey participants was issued from May 27, 2020 to August 31, 2020. Approval included permission to survey participants online using the Jisc Survey platform to build and distribute the survey to Participants. Page one of the survey consisted of participant information explaining that participation was not mandatory. Additionally, participants were informed of the potential bioethical concerns with the included image from the Pernkopf Atlas. After reading the participant information, participants confirmed their consent by hitting next. They could exit the survey at any time before submission if they changed their mind. Only data of the participants who hit submit were recorded.

The survey was designed to compare the newly created visualisation to past medical visualisations. The past visualisations were chosen by looking for

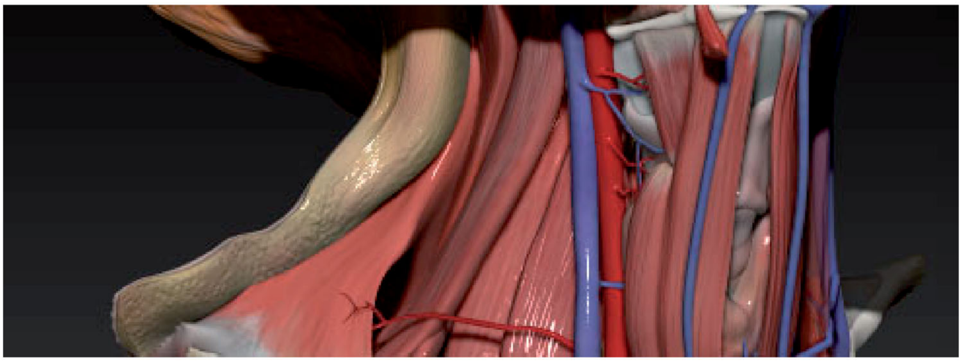


Figure 9. Finalised muscles after being refined multiple times.

the closest possible matches to the Pernkopf illustration and were created by Frank Netter (Netter, 2003, p. 28) and Henry Carter (Gray, 1918, p. 576) of the Posterior Cervical Triangle. Dr. Mackinnon identified the Pernkopf image used in the survey. The image can be accessed through the *St. Louis Jewish Light Newspaper* (Berger, 2020, Left); the Netter image can also be accessed here (see Berger, 2020, Right). The new image was rendered and output in ZBrush. The images were saved privately on the author's website and added to the survey using a link generated by the website. The multiple choice questions were intended to gauge general participant preferences and attempted to retain parallelism between sections. The multiple choice questions were analysed and sorted using the built in sort scripts available in Jisc survey software. Open-ended response questions were optional and available to participants who felt a need to expand on their reasoning for the multiple choice responses they selected. The open-ended responses were analysed using thematic analysis (Braun & Clarke, 2006). Open-ended responses were reviewed to establish some familiarity with the content of the responses. Then the responses were brought into a Microsoft Word Document where they were parsed for similar words and statements. The consistent words and ideas were highlighted using different colours and then after parsing the information a second time, a rough draft of a mind map was created. From the preliminary mind maps, more finalised names for the themes and subthemes were developed and formatted in an official mind map (see Figure 10).

Once the data was collected, it was sorted based on participant groups (i.e. Professionals vs. Students, Artistic vs. Medical/Anatomical participants, etc.) to see if any patterns could be identified. Although most trends in preferences were consistent between groups, when the data was sorted to compare the 26 participants with an artistic background (professional medical artists, medical art students, forensic art students, and biological illustration students) versus the 52 participants with a medical/anatomical background (CAHID anatomists, CAHID anatomist students, a medical doctor, medical students, and surgeons), specific trends were identified in several of the questions' answers. These trends are formatted in separate tables below the main data set in each section. Full colour versus partial colour was not defined for participants and colour blindness was not taken into account for any section of the survey comparing full colour to partial colour. The open-ended questions are addressed separately from the multiple choice questions in the tables in the Thematic Analysis section under Results and under the Discussion section.

Results

A survey was distributed between July 2 and July 20, 2020 and 78 total responses were received. Of the 78 participants, there were (Question 1): 36 medical students, one medical doctor, 11 medical art/illustration students, nine medical art professionals, three forensic art students, three Centre for Anatomy and Human Identification (CAHID) anatomy students (having completed one module of gross anatomy), three CAHID Anatomy Staff, three third- and fourth-year Biological/Pre-Medical Illustration Students (BPMI), and three surgeons (see Table 1). Participants were asked to respond to 22 questions: 18 required multiple choice questions and four optional open-ended questions.

Survey section 1

Section 1 of the survey consisted of five multiple choice questions (Questions 2, 3, 4, 5, and 7) and one open-ended question (Question 6), which had participants compare four images (see Table 2). For the purposes of writing this section, where the word 'figure' was used in the survey it is substituted with the word 'image' to decrease confusion with the figures in this paper. Image 1 (Netter) (Netter, 2003, p. 28) and Image 2 (Pernkopf) (Berger, 2020, Left) can be accessed through the *St. Louis Jewish Light Newspaper* because it is one of the few places that the Pernkopf illustration is accessible online, Image 3

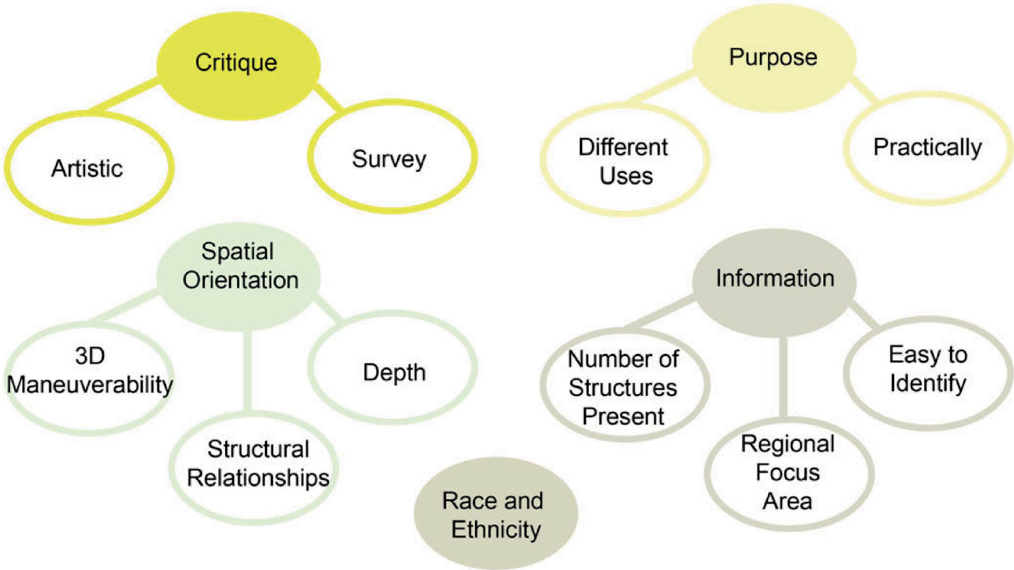


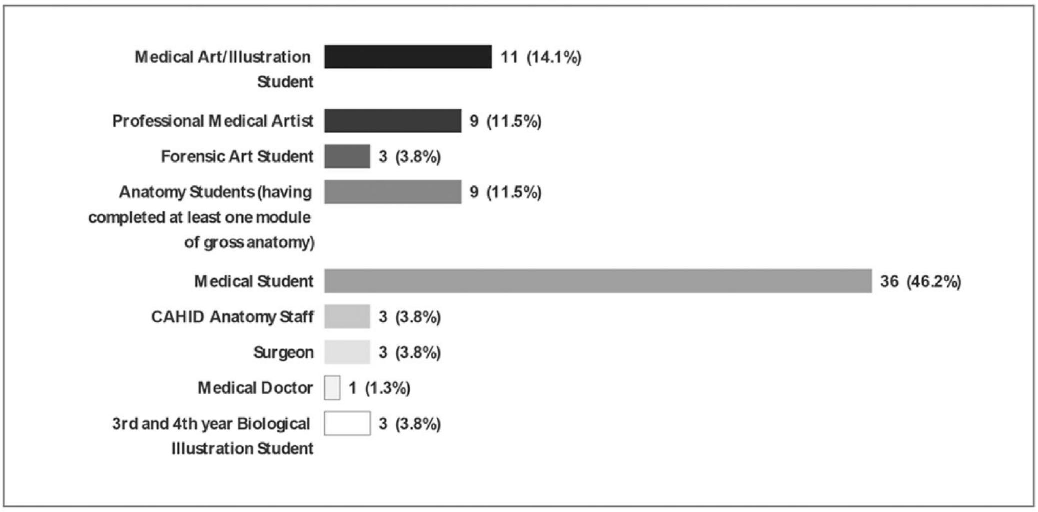
Figure 10. Thematic analysis: themes and subthemes.

Table 1. Survey participant background.

Survey Results

Total Participants: 78

1 Please list your field of expertise or study

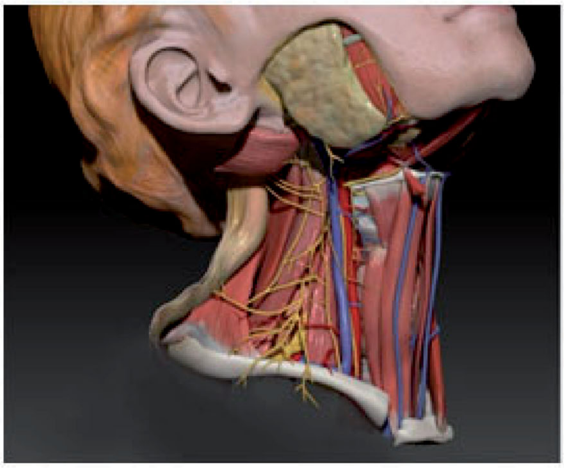


(New Image) was the new image developed for this project, and Image 4 (Grey) was taken from Grey's Anatomy (Gray, 1918, p. 576). Of the images, Image 2 (Pernkopf) was overarchingly considered the most detailed, with 65% of participants selecting it (Question 2). For Question 4, which asked about anatomical accuracy, Image 2 (Pernkopf) and Image 3 (New Image) were the most preferred images, with Image 2 being preferred at 46.2% and Image 3 being preferred at 35.9%. Image 3 (New Image), was preferred for highest quality (Question 3) and easiest to understand (Question 5). For Question 7, 69.2% of participants preferred full-colour and 30.8% preferred partial colour. Question 7 is not included in the discussion as it had poorly defined parameters of what constituted full-colour or partial colour. Similar questions from Section 2 of the survey better address participants' preference for full-colour or partial colour.

When the data from Section 1 of the survey was sorted into participants from an artistic background and participants from a medical/anatomical background, responses differed between groups, particularly for Question 4. Participants from an artistic background significantly preferred Image 2 (Pernkopf) for anatomical accuracy, where participants from a medical/anatomical background were divided between Image 2 (Pernkopf) and Image 3 (New Image) (see Table 3).

Table 2. Survey Section 1: Questions and results (Images 1 and 2: (Berger, 2020); Image 4:(Gray, 1918, p. 576)

IMAGE 1 (Netter) IMAGE 2 (Pernkopf)



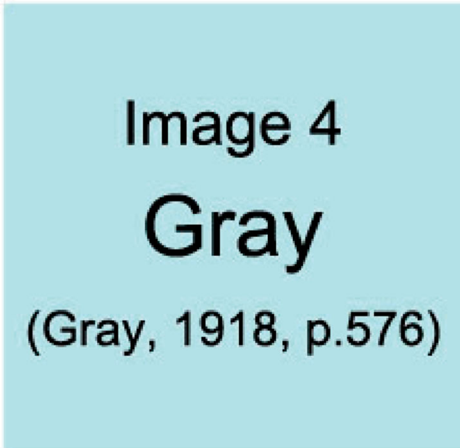
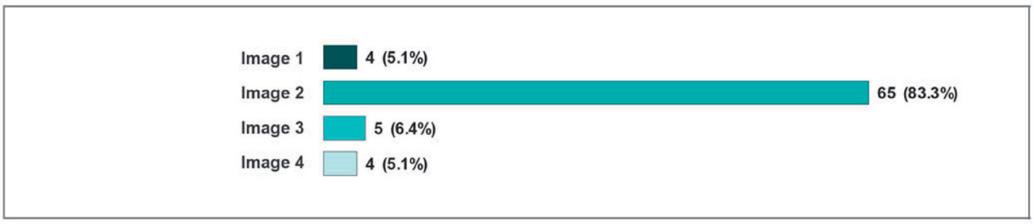


IMAGE 3 (New Image) IMAGE 4 (Gray)

Section 1: Looks at existing resources and compares them to the newly created resource

2 **Of images 1-4, which image seems the most detailed?**

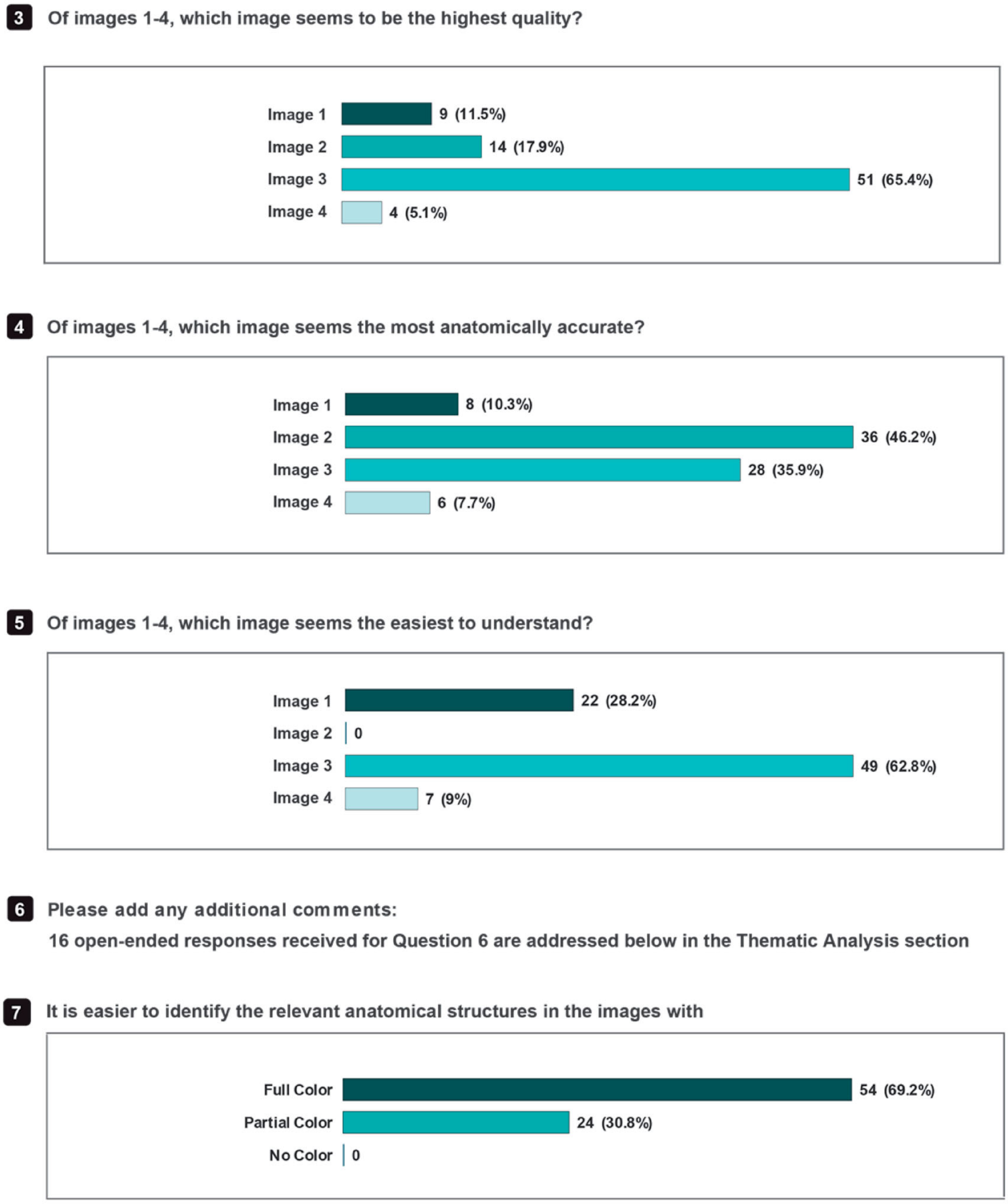


(*continued*)

Survey section 2

Section 2 of the survey consisted of five multiple choice questions (Questions 8, 9, 10, 11, and 12) and one open ended question (Question 13), which had participants compare two different styles of the new visualisation created for this thesis: Style 1 in full colour versus Style 2 in partial colour. Participants chose Style 1 as the most detailed and selected Style 2 as the easiest in which to identify structures (Questions 8 and 9). Participants preferences for revision/studying, dissection, and surgery were more evenly selected (Questions 10, 11, and 12) (see Table 4).

Section 2 showed the highest number of differences between participant groups (see Table 5).



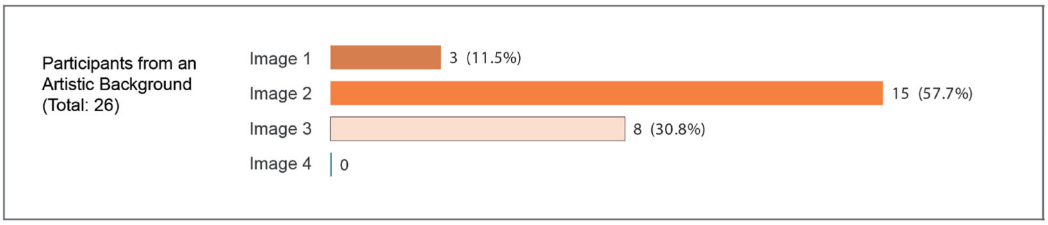
Question 9 showed participants from an artistic background overwhelmingly preferring Style 2, with medical/anatomical participants showing a more evenly divided preference between the two styles. Question 10 showed a similar trend, with artistic participants preferring Style 2 (less significant than their preference in Question 9) for studying and medical/anatomical participants preferring Style 1. The same trend in preference was shown for Question 11, on dissection, between the two groups.

Survey section 3

Section 3 of the survey consisted of nine multiple choice questions (Questions 15, 16, 17, 18, 19, and 21) and two open-ended questions (Questions 20 and 21.a), which had participants compare the new visualisation formatted for this thesis in two different ways: Resource 1, 3D model and Resource 2, 2D model (see Table 6). Participants majorly preferred Resource 1 (3D), except in dissection situations.

Table 3. Survey Section 1: Differences between groups (Question 4), difference in responses to Question 4, by participants from an Artistic Background and a Medical/Anatomical Background

4 **Of images 1-4, which image seems the most anatomically accurate?**



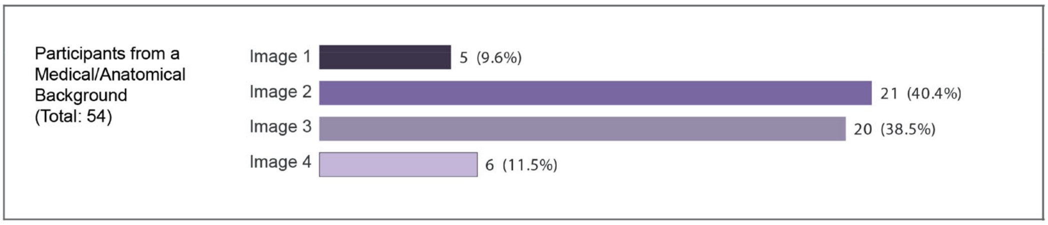
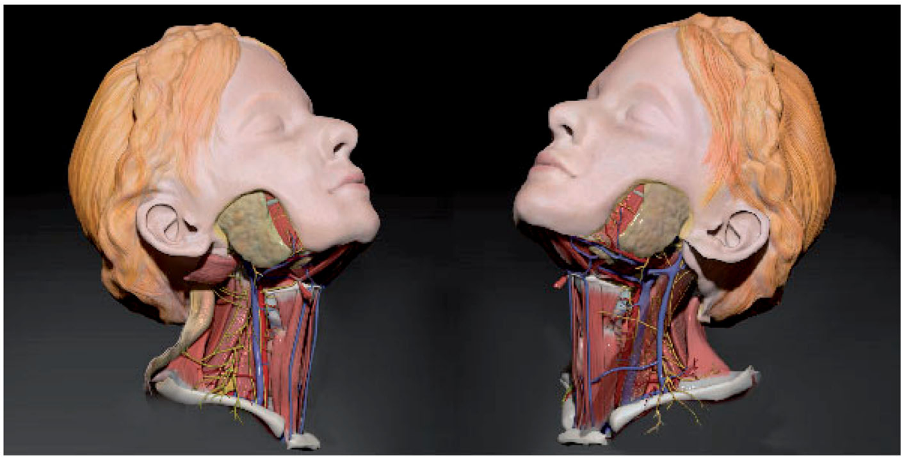
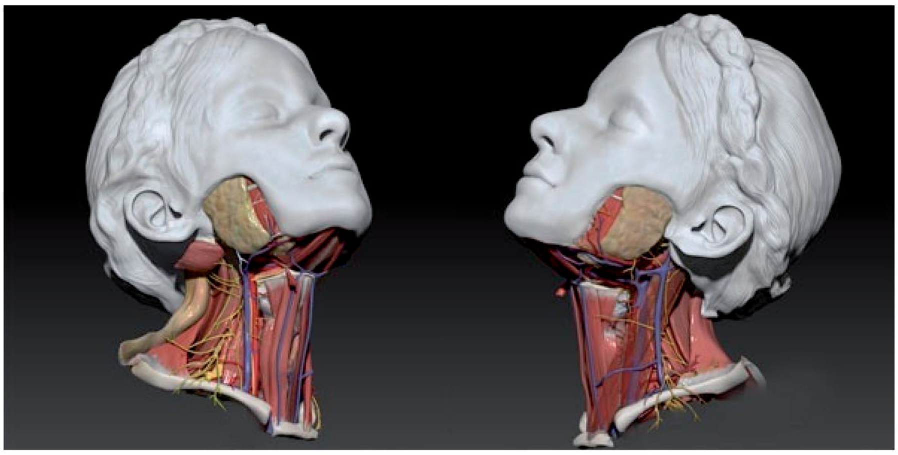


Table 4. Survey Section 2: Questions and results.



STYLE 1



STYLE 2

(*continued*)

There was one main difference identified between the participant groups in Section 3 for Question 18 (see Table 7). While overall Resource 2 (2D) was preferred for dissection, participants from a medical/anatomical background showed a slight preference (53.8%) for Resource 1 (3D) in dissection situations. This stands in contrast to the large percentage of participants from an artistic background (69.2%) that preferred Resource 2 (2D).

Thematic analysis

Five main themes were identified using thematic analysis to parse the open-ended responses; subthemes were identified for each main theme (see Figure 10). There was overlap between themes in some responses, while some open-ended responses were excluded from the discussion because they were incomplete, which

Table 5. Survey Section 2: Differences between groups (Questions 9, 10, 11). Difference in responses to Question 9, 10, 11 by participants from an Artistic Background and a Medical/Anatomical Background

made them unclear. The themes and subthemes identified in the open-ended questions include:

a. Critique.
   - Survey.
   - Artistic.
b. Purpose.
   - Different uses.
   - Practicality.
c. Information.
   - Number of structures.
   - Easy to Identify.
   - Focus areas.
d. Spatial orientation.
   - 3D manoeuvrability.
   - Depth.
   - Structure relationships.
e. Race and ethnicity.

Discussion

Several new and old medical illustration methods were identified as having been successful including depth, detail, and 3D mediums. Additionally, some unexpected perceptions were expressed in the open-ended responses and supported through the multiple choice answers.

Survey section 1 (information)

When asked which was the most detailed of the four images in Section 1, participants showed significant preference for the Pernkopf Atlas (Question 2) (Image 2, refer to (Berger, 2020) left). When about the quality of the images and the ease of understanding participants strongly preferred Image 3 (Question 3 and 5): '[Image] 3 seems to be the best at eliminating the noise'. In regards to ease of understanding, it should also be noted that Image 1 (Netter, refer to (Berger, 2020) right) was preferred second to Image 3 (New Image), which is expected given that Image 3 (New Image) only integrated a few additional structures relative to the number included by Netter in Image 1. Time restraints limited the number of nerve branches that could be included in Image 3. The biggest difference between Image 1 (Netter) and Image 3 (New Image) was the amount of depth conveyed in Image 3, because it was exported from a 3D model.

Many decisions for preference in Section 1 seemed dependent on the amount of information included in the individual visualisations. In regards to the detail in Image 2 (Pernkopf), one participant noted:

> There is a level of detail in [Image] 2 that is not present in the rest of the images. It shows a lot more anatomical variation of the singular person it was made from as well as more branches of each of the structures (nerves, veins) … I believe it might be detrimental for smaller structures should anatomical variation be present …

Another open-ended response commented on Image 3 (New Image), 'In all the traditional illustrations, information is lost with all the detail the artists felt they needed to portray of th[e] musculature fibers'. Both of these responses indicate that the detailed rendering the Pernkopf Atlas includes may be unnecessary for achieving an illustration considered equally as detailed. To explore this further, more nerve branching could be added to the new resource and a second survey could be taken to determine if the new level of detail is equal to that of the Pernkopf Atlas.

Survey section 2 (information and race and ethnicity)

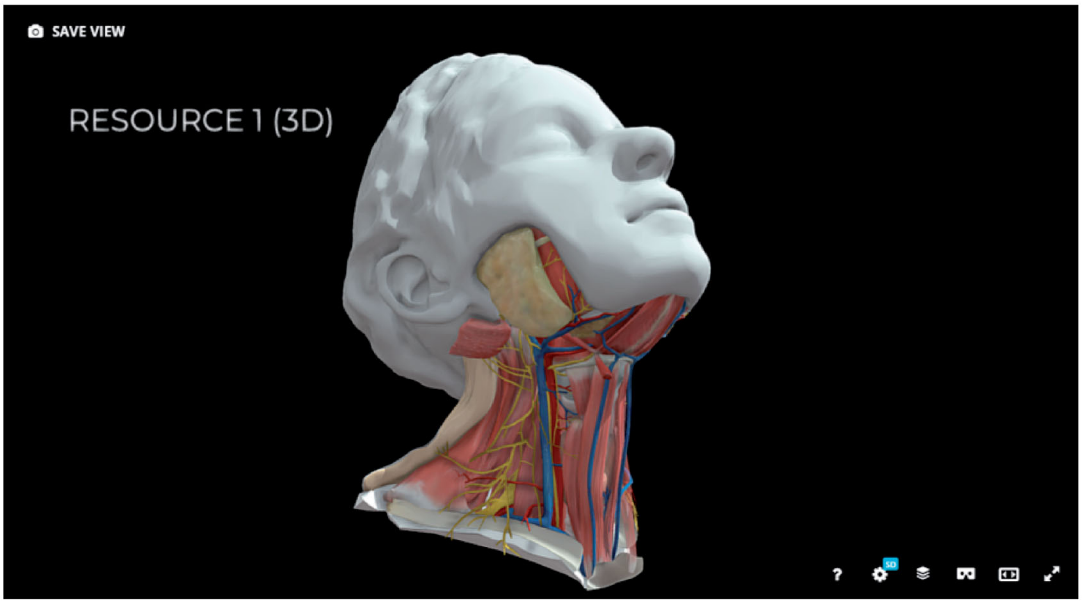
Although there was not a significant preference shown for Style 1 over Style 2 in Section 2 of the survey, there were distinct differences in the preferences shown between groups. Participants from an artistic background showed a preference for Style 2 (greyscale) in Questions 9, 10, and 11. Alternatively participants from a medical/anatomical background preferred Style 1 (colour) in Questions 9, 10, and, 11 (see Table 5). The preference shown by artistic participants for Style 2 (greyscale) in Questions 9, 10, and 11 suggests that their existing knowledge of visual mechanisms employed by artists to draw a viewer's eyes may have influenced their choice. This is further supported by the open-ended responses received from artistic participants in this section: Five of the six comments received discussed how the greyscale option drew the eye to the neck; only one comment received from medical/anatomical participants recognised the intent of this method.

When participants from a medical/anatomical background expressed interest in Style 2 (greyscale), it was more often for reasons relating to ethnicity. During thematic analysis, one theme that continuously arose, specifically in Section 2, was race and ethnicity. Comments that were received suggested using more ethnicities in medical visualisation or using styles like that of Style 2 to mask the ethnicity of the people in the visualisation. Four of the 14 total comments specifically addressed race and ethnicity; three of those four comments were received from participants with a medical/anatomical background: 'I think the second image is preferable because with some minor changes to the hair, it could be neutral in terms of race/ethnicity.'

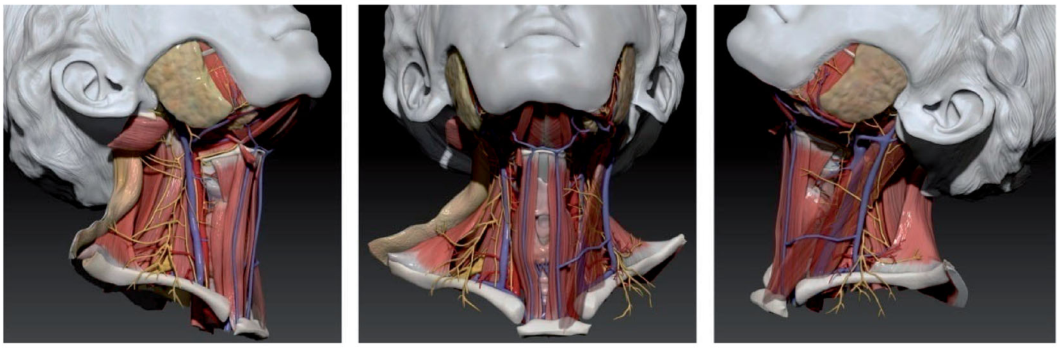
Survey section 3 (spatial orientation and purpose)

It was noted in the literature review that 3D visualisations may be the best method for creating medical illustrations as the field progresses. Past studies have shown positive reactions by students and professionals when evaluating 3D models and resources (Hackett & Proctor, 2016). The precedent set by these studies was corroborated by the data collected in Section 3 of the survey for this thesis. Through the multiple choice questions and the open-ended responses in Section 3, participants showed a significant preference for the 3D resource in terms of detail, ease of understanding, and revision/studying. The only place where the 3D resource was not clearly preferred was for dissection. Many participants expressed concern that it would require degloving or contaminating a screen (Question 18) (see Table 2). Participants may have answered differently if they had known it is permissible to contaminate the screen during dissection.

Table 6. Section 3 questions and results.



RESOURCE 1 (3D) | View: https://skfb.ly/6TXKL



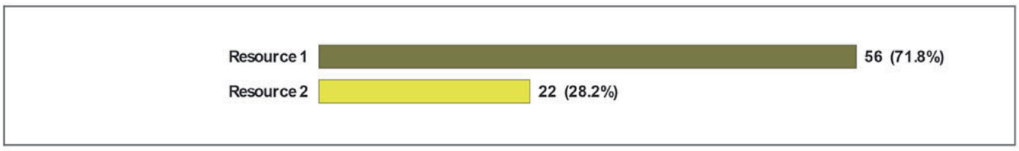
LEFT CENTER RIGHT

RESOURCE 2 (2D)

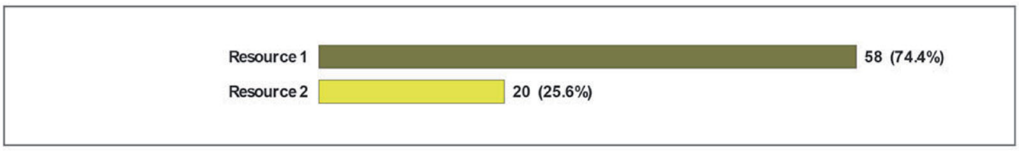
Section 3: Analyzes preferences between 2D and 3D resources created

(3D) - Resource 1 (2D) - Resource 2

14 Of resource 1 or 2, which resource seems the most detailed?

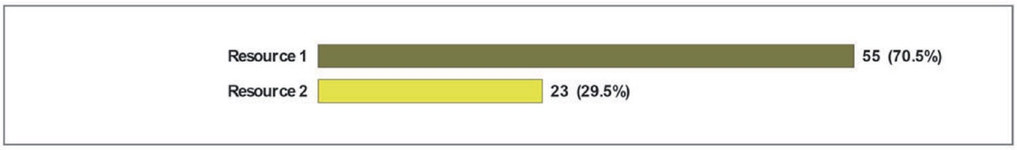


15 Of resource 1 or 2, which resource is the easiest to understand?

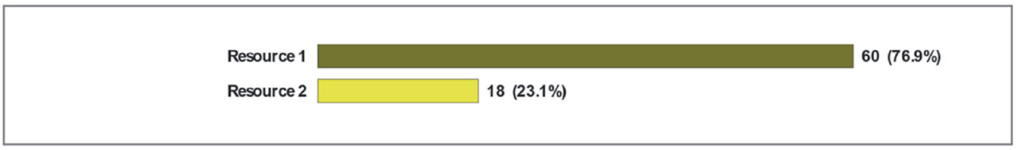


(*continued*)

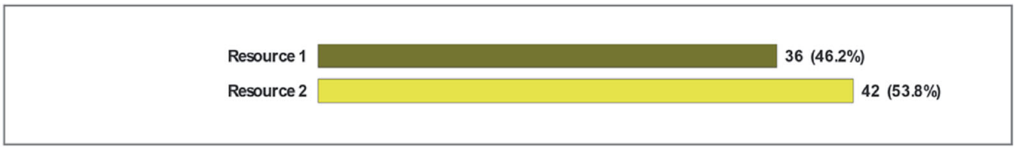
16 Of resource 1 or 2, which resource seems the most anatomically accurate?



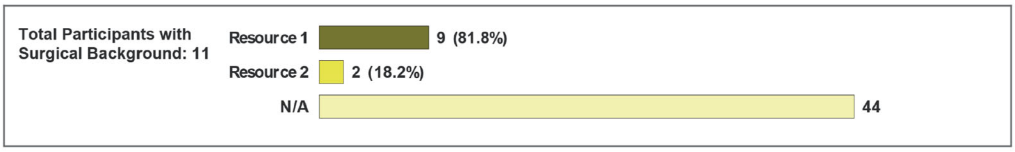
17 Of Resource 1 and 2, which resource would you rather use for revision/studying (revision is the UK term for studying)?



18 Of resource 1 or 2, Which resource seems the most practical for reference during a dissection?

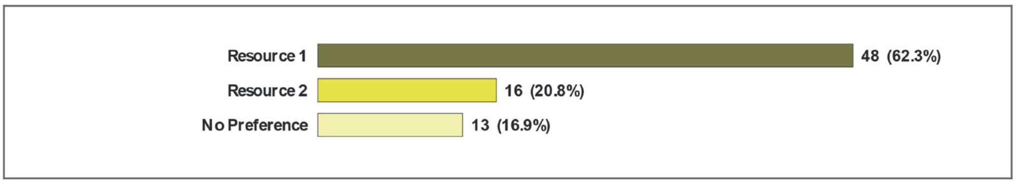


19 Only answer if you have surgical experience: Of resource 1 and 2, which resource seems the most practical for reference during a surgical operation?



20 Please add any additional comments
14 open-ended responses received for Question 20 are addressed below in the Thematic Analysis section.

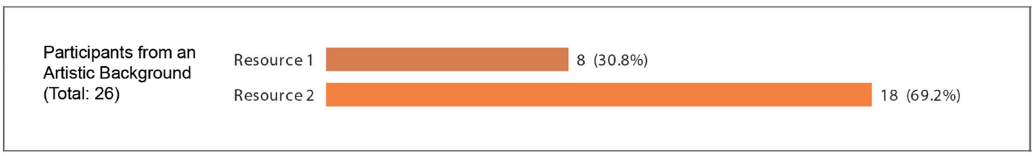
21 Of the resource 1 and 2, which do you prefer?

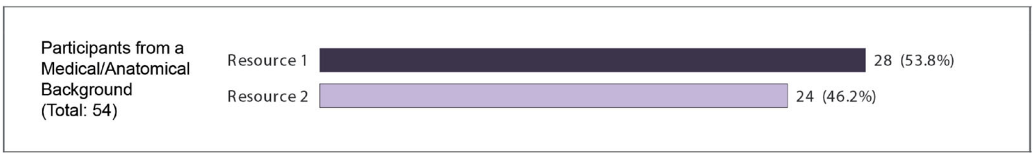


21 a. Please add any additional comments
10 open-ended responses received for Question 21a are addressed below in the Thematic Analysis section.

Table 7. Survey Section 2: Differences between groups (Question 18)

18 Of resource 1 or 2, Which resource seems the most practical for reference during a dissection?





Potential study limitations (critique)

When reviewing the survey results several potential limitations of the study were identified: unequal formatting of the four figures in Section 1 of the survey and confusion in how to interpret questions throughout the survey.

Unparallel formatting

The participants noted that the Images, 1, 2, and 4 were not the same resolution as Image 3 (the image created for this thesis). Some participants expressed concern that this may have lead to difficultly determining which image was the highest quality, creating bias towards Image 3 (New Image), in Question 3: 'The "highest" quality in particular was difficult because the resolution to the 2D illustrated examples are lower resolution, so I am getting less detail than perhaps they actually are.' Due to lack of direct access to the original illustrations, higher resolution sources of the other images (Image 1 (Netter), Image 2 (Pernkopf), and Image 4 (Grey)) were difficult to attain.

Question confusion

Several participants also expressed difficulty interpreting questions throughout the survey, calling for the terms used to be better defined or noting that a difference in interpretation would have changed how they answered the questions. A participant noted in Section 1, 'For question 3 I took quality to mean anatomical realism. However, I would have picked [Image] 3 perhaps if the context is learning resources for a basic level of anatomy'. Most participants, who commented on why they selected Image 3 (New Image) in regards to quality and ease of use, noted Image 3 had a 'clean finish' and was successful at 'eliminating the noise'. This indicates that using the 3D style of Image 3 (New Image) while adding more anatomical structures may create a visual that is as useful as Image 2 (Pernkopf). So instead of rendering everything to the highest level of detail as the Pernkopf Atlas did, focussing more on the relevant structures may be the solution to creating a highly detailed and understandable resource.

Effective methods identified

The objective of the survey was to identify past and present methodologies that are well received by the people who utilise and create medical art. Three main methods that contribute to a successful medical visualisation were identified from the results of the survey.

Depth

In the past, strong drop shadows were used in an effort to convey depth and the relative position of structures. Now using 3D modelling, this is more easily accomplished because the structures are built deeper than the superficial structures. 3D models do not rely on 2D illusions to attain this look.

Detail and balance

While it has always been known that an effective visualisation is dependent on a balance of detail and relevant material, the Pernkopf Atlas is most notable for the number of structures it contains. However, in this study it was shown that none of the 78 participants felt it was the easiest to understand (Question 5) (Table 1). The new image which was preferred for ease of understanding unintentionally included less branching in the nerves and vessels due to a time limitation. It should therefore be noted that the lesser number of structures may have influenced participant's choice in preferring the new resource for ease of understanding. However, participants noted their preference for the new image in part to the sense of depth created by the 3D rendering. If the 3D nature of the new resource makes it easier to understand, this style of visualisation could work to create a more effective illustration than that found in the Pernkopf Atlas. While professionals and upper level students may need resources with a larger number of structures to reference anatomy, that does not necessarily mean they favour visualisations with the highest level of rendering like the Pernkopf Atlas. This leaves questions that could be pursued in future studies.

3D Models

The overarchingly positive reaction to the 3D resource indicates that 3D models should be made more available for use by anyone needing to study or reference anatomy, ranging from patients, students, professionals, and surgeons (with the content included adjusted to the appropriate audience level).

Future work

There are many ways these findings could be explored further in the future, either through the replication of this study or through additional research into different variables identified in this study. This study's limitations could be adjusted for a new study by trying to use consistent language and visuals and looking to include more surgeons in the participant base. Surveying surgeons would help to address the needs of surgical professionals as opposed to medical students. Given that the Pernkopf Atlas fits a surgical need more than a teaching need, more work is necessary to understand what it provides for surgeons that other atlases do not.

Rather than focussing on past medical illustrations, research could be conducted by focussing on the individual variables identified in the survey. This could help clarify definitions of terms such as quality and detail. For instance, detail could be explored by using the same base image that includes progressively more structures to gauge the ideal level of detail for different types of participants. This could also be applied with the level of detail with which muscles are rendered.

Conclusion

The newly created resource may not compare to the Pernkopf Atlas in terms of detail and realism, but through the data collected on different participants' style, medium, and detail preferences, some of the successes and failures of past and present medical visualisation methods were identified:

1. The importance of depth for understanding spatial relationships between structures.
2. Balanced detail for successfully highlighting the relevant information in an illustration.
3. 3D mediums for better spatial orientation.

Participants showed a high preference for the new visualisation in terms of quality and ease of use. They also showed a high level of preference for the 3D model created over the 2D visualisations output from the model. This may have been partially influenced by the resolution of the new image compared to the other images included in the survey. Pernkopf's illustration still ranked higher in terms of detail. Participants did note confusion when defining 'quality' (Question 3). It was expected that the greyscale style would be more widely preferred by all participants, however, only participants from an artistic background showed a strong preference for the greyscale style. This indicated that other methods of highlighting relevant information may be more effective than the greyscale method employed in the new image and by Pernkopf. This study has identified some tangible qualities to help better determine the balance of conveying detail and relevant information.

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