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Visualizing Visual Neural Pathways in Virtual Reality A Neuroanatomy Tool

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Medical Illustration

Visualizing Visual Neural Pathways in Virtual Reality
A Neuroanatomy Tool

by

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Visualizing Visual Neural Pathways in Virtual Reality - A Neuroanatomy Tool

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Abstract

Visualizing the human brain and its structures in three dimensions is a complex and overwhelming task. Sensory pathways such as visual neural pathways, are important but difficult to visualize. With the rising popularity of extended reality (XR) in modern education, a Neuroanatomy tool in virtual reality (VR) was developed to allow students and other learners to explore the human brain and learn about its functions in an engaging way. Virtual reality enables a user to have the ability to visualize complex structures in the brain in a way that is otherwise impossible to see in a cadaver lab or web-based resources. By implementing this completely immersive and interactive learning style, individuals will be able to effectively learn at their own pace with clarity.

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II. Introduction

Neuroanatomy is considered to be one of the most difficult subjects for students (Javaid et al., 2018). The visualization of the human brain in three dimensions is a challenging task due to the vast network of neural pathways. Sensory pathways, such as visual neural pathways, are an essential topic for understanding the mechanisms of sensory perception. Current traditional neuroanatomy teaching strategies are limited by a lack of effective and accurate resources. As a result, students may become disengaged from the learning process which can lead to poor performance in exams and a lack of understanding of the subject matter. This knowledge gap in neuroanatomy has caused clinicians to worry about the future of healthcare (Waterston & Stewart, 2005). If doctors and other healthcare professionals do not have a strong understanding of neuroanatomy, their ability to diagnose and treat patients may be negatively impacted. The use of virtual reality (VR) is one promising way to address the limitations of traditional neuroanatomy teaching strategies. In response, an interactive neuroanatomy tool in VR was developed. This tool allows learners to explore an accurate representation of the brain structure in a 3D environment through brain cross-sections in the sagittal, transverse and coronal planes. Users are able to view structures involved in the visual neural pathway and be guided through learning modules to understand how vision is processed. The goals and objectives of the neuroanatomy tool are to enhance a user's understanding of the visual neural pathway, provide an accurate and comprehensive visualization that is effective in representing visual pathways and to increase a student's knowledge and ability to retain information about visual pathways. The field of VR has experienced exponential growth in recent years, leading to a wide range of applications across diverse industries. Some examples in the medical industry include surgical training, anatomy education and communication skills training. Although the use of VR in medical education is still in its early stages, it has the potential to revolutionize the way learners and healthcare professionals are trained. As VR technology continues to develop, it is likely that VR will become increasingly popular in medical education.

III. Scientific Background

A) Visual Neural Pathways

The primary visual neural pathway can be summarized as a sequential process beginning with light stimuli being converted into electrical signals and processed by the retina. The electrical signals are then relayed through the optic nerve for further processing and filtering in the lateral geniculate nucleus of the thalamus. The visual signals then are delivered via the optic radiation to the visual cortex. The visual cortex analyzes and interprets the visual information by extracting and integrating features and contributing to our visual perception of objects (Mahabadi et. al., 2022).

In order to fully understand the visual neural pathway, it's important to identify and understand key terminology, structures and concepts associated with it.

1. Retina

The retina is a multilaminar structure located near the posterior portion of the eye. Its main function is to convert light energy into neural signals, enabling vision. The retina consists of nine distinct layers, each contributing to the process of visual perception. The layers of the retina can be classified based on their position from the posterior to the anterior region of the eye (Mahabadi et. al., 2022).

Layer of Photoreceptors

The first layer of the retina contains two types of photoreceptor cells called rods and cones. These photoreceptor cells are responsible for converting light into electrical signals. Rods are highly sensitive to low-intensity light and play a role in peripheral vision and our ability to detect objects and objects' motion at low light levels in shades of gray (Nieuwenhuys, 2008). This is a visual phenomenon known as scotopic vision. Cones, on the other hand, are responsible for perceiving light at higher intensities and are involved in color vision, which is known as photopic vision. There are three types of cones: L cones, M cones, and S cones (Nieuwenhuys, 2008). L cones are sensitive to long wavelengths of light and are responsible for perceiving the color red. M cones are sensitive to medium wavelengths and perceive green colors. Lastly, S cones are sensitive to short wavelengths and perceive the color blue. Compared to rods, cone cells have the advantage of quickly adapting to changes in light conditions.

Outer Limiting Membrane

The retina's second layer is the outer limiting membrane. It is composed of a unique junction complex created by Muller glial cells. Also referred to as radial glial cells, these cells form adherens junctions that connect with the inner segments of the photoreceptor cells (Nieuwenhuys, 2008).

Outer Nuclear Layer

In the third layer of the retina is the outer nuclear layer which houses the nuclei of the photoreceptor cells. This layer serves as a home for the cell bodies of rods and cones.

Outer Plexiform Layer

The fourth layer of the retina is known as the outer plexiform layer. In this layer, synaptic connections are facilitated between photoreceptor cells and horizontal cells (Nieuwenhuys, 2008). It serves as a hub where the dendrites of bipolar cells and other interneurons receive input from rods and cones. Additionally, this layer accommodates a network of capillaries to ensure proper blood supply to the retina.

Inner Nuclear Layer

The inner nuclear layer of the retina is the fifth layer and contains the nuclei of various cell types including bipolar cells, horizontal cells and amacrine cells. Bipolar cells establish connections between cones and ganglion cells, which ultimately give rise to the axons of the optic nerve. Horizontal cells, on the other hand, form synapses with photoreceptor cells which contribute to the regulation of visual information processing (Kim, 2021). Both horizontal cells and amacrine cells are non-spiking inhibitory neurons (Kolb, 2007). This means that their primary function is to regulate activity of other neurons in the retina by inhibiting their firing rates.

Inner Plexiform Layer

The sixth layer of the retina, known as the inner plexiform layer is primarily composed of amacrine cells. These cells receive input from other amacrine cells as well as bipolar cells to form neural connections that contribute to various visual functions (Kolb, 2007). These functions include detecting changes in motion and encoding information related to color and contrast.

Ganglion Cell Layer

The ganglion cell layer is located in the seventh layer of the retina and lies closest to the vitreous humor. The vitreous humor is a transparent, gelatinous substance that provides support to the retina (Murthy, et. al, 2014) Within this layer, ganglion cells receive visual information from bipolar cells and amacrine cells which act as interneurons in the visual pathway. The ganglion cells play a critical role in processing graded potential signals into action potentials which are transmitted through the optic nerve. These signals are then used to create our visual perception. Moreover, ganglion cells serve other functions such as detecting specific visual stimuli like contrast and motion. (Kim, et. al, 2021)

Layer of Optic Nerve Fibers

The eighth layer of the retina consists of a bundle of nerve fibers which collectively form the optic nerve. These nerve fibers transmit visual information from the retina to the brain to be further processed. As the optic nerve exits the eye, it passes through the optic disc, a region commonly known as the blind spot. This region lacks photoreceptor cells and therefore, lacks the ability to process visual stimuli.

Internal Limiting Membrane

The final layer of the retina is the internal limiting membrane, which separates the vitreous humor from the retina. Composed of Muller cells, it maintains the structural integrity of the inner retina, providing support for the cells to ensure proper organization and positioning.

2. **Optic Nerve**

The optic nerve is a bundle of nerve fibers that originated from retinal ganglion cells. This nerve carries visual information from the retina and travels to the optic chiasm.

3. **Optic Chiasm**

The structure where the optic nerves cross is known as the optic chiasm. Located at the base of the brain, the nasal retinal fibers originating from both the left and right eyes cross to the opposite tract to establish a contralateral connection (Nieuwenhuys, 2008). On the other hand, temporal retinal fibers maintain their path within the same optic tract, thus maintaining an ipsilateral pathway.

4. **Lateral Geniculate Nucleus (LGN)**

The lateral geniculate nucleus is one of the most important structures for processing visual information (Covington, 2022). It is located in the thalamus, a structure that is superior to the mesencephalon (Torrico, 2022). It receives visual information from the optic nerve and sends it to the primary visual cortex in the occipital lobe.

5. **Optic Radiations**

Visual information is relayed from the lateral geniculate nucleus through the optic radiations which are a bundle of nerve fibers that transfer neural signals to the visual cortex (Covington, 2022).

6. **Meyer's Loop**

Meyer's loop is a segment of the optic radiation that wraps around the temporal horn of the lateral ventricle. Located within the temporal lobe of the brain, this area enables optic radiations to transmit information to the primary visual cortex (Nieuwenhuys, 2008). Axons responsible for carrying information pertaining to the superior visual field pass this region.

7. **Visual Cortex**

The primary visual cortex is specifically known as V1 and is situated at the posterior side of the brain in the occipital cortex. This structure plays an important role as it serves as the primary cortical region responsible for receiving visual information. Its main function revolves around processing shapes, color and brightness (Nieuwenhuys, 2008). Subsequently this information is conveyed to other cortical areas where it goes through further processing and interpretation.

B. Existing Media Analysis

Current neuroanatomy tools lack accuracy and level of detail of the brain. Existing models are primarily static 2D images or 3D representations that fail to fully capture the intricate complexity of the brain. As a result, there is a growing need for an advanced method to visualize the brain and its neural pathways. This need is crucial in education where accurate visualizations play a key role in facilitating student learning and comprehension. Efforts have been made by groups and universities worldwide to address this challenge through the development of their own neuroanatomy online and virtual reality applications. However, the existing virtual reality applications still suffer from limitations.

The UW Virtual Brain Project, developed by Visual Reasoning Lab at the Wisconsin Institute for Discovery, aims to explore how visual reasoning contributes to visual communication. Their application immerses users in a dark, gridded virtual reality environment, where a floating light blue brain, devoid of its cerebral cortex, is centered. As the experience progresses, the brain turns transparent to reveal the structures involved in the visual pathway. A narration accompanies the experience, explaining the significance of the visual pathway and its relevance to our daily lives. Each brain structure associated with the visual pathway is clearly labeled, and users are guided through each area to understand how vision is processed.

The unique approach of presenting the brain with different quadrants, color-coded to correspond with eye processing, proved successful. However, the 3D model of the brain could benefit from improvements in terms of cleaning and refining its design. Additionally, the tool could be enhanced by implementing captioning for a more inclusive experience. Despite these areas for improvement, the UW Virtual Brain Project remains an innovative tool for showcasing and understanding the visual pathway's complexities.

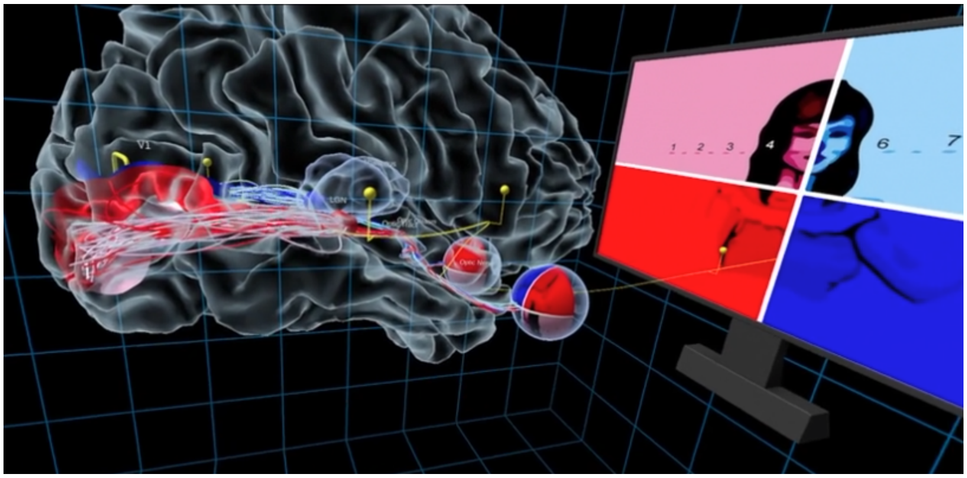


Figure 1. Demonstration of UW Virtual Brain Project's virtual reality application.

IV. The Body of Work

A. Project Objectives

The objectives of the interactive neuroanatomy tool in virtual reality are to:

- Enhance a user's understanding of the visual neural pathway through user-selected sections in brain areas involved in vision in a virtual reality environment.
- Provide a comprehensive, three-dimensional visualization that is accurate and effective in representing visual pathways.
- Increase a student's knowledge and ability to retain information about visual pathways.

B. Ideation and Wireframing

Wireframing is a critical step in the development of any app by providing a visual blueprint that outlines the structure, layout and functionality of the application. In the initial stages, a series of preliminary sketches were developed in Procreate to provide a basic visual framework depicting the envisioned appearance of the virtual reality application. The design process involved an extensive exploration of relevant literature on human depth perception and field of vision to aid the design with evidence-based insights. Subsequently, the rough preliminary sketches went through refinement within Figma, an interface design tool. The refining phase aimed to clarify the objectives of the application and produce a polished representation that communicated the intended concept.

Figure 2. Preliminary sketch of the Neuroanatomy tool featuring basic user interface elements, a lab bench and brain.

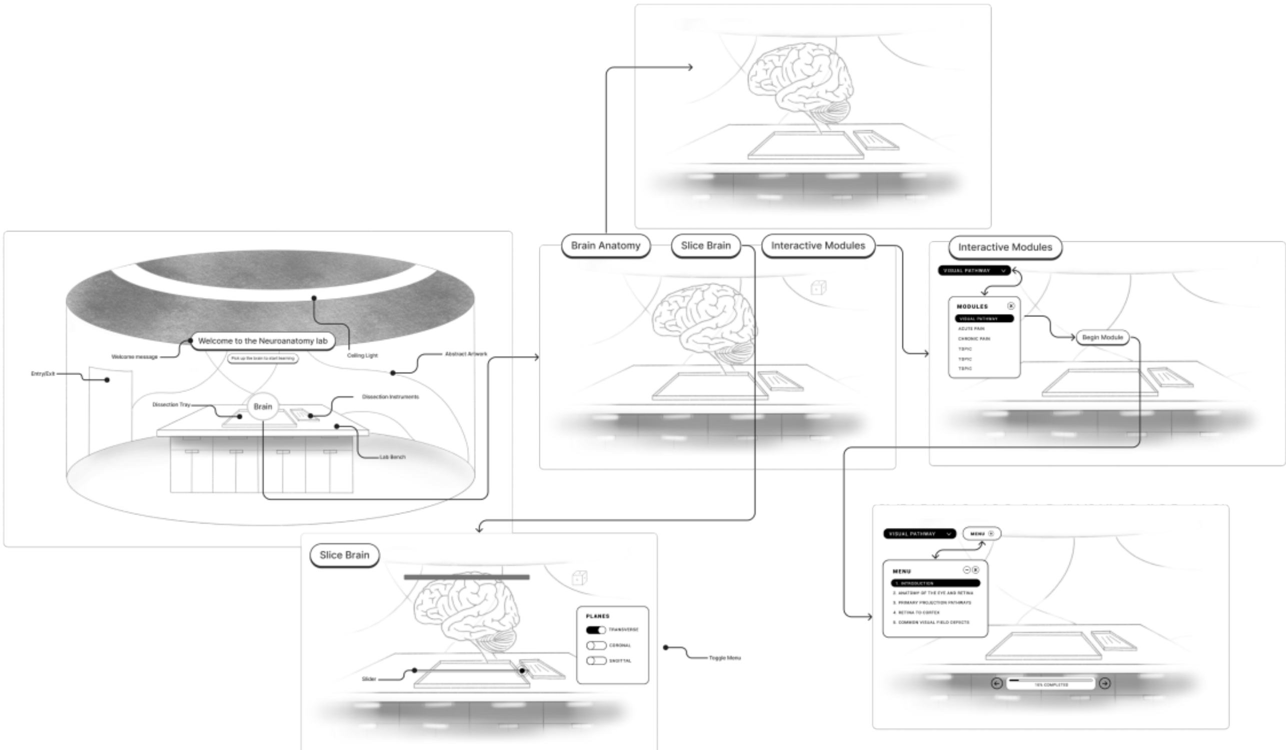


Figure 3. Wireframe and sketches completed in Figma and Procreate. Basic UI design exploration laid out possible modules and environment design.

C. User Interface Design and Experience

Extensive research was conducted to explore effective strategies for creating a successful immersive VR experience. However, due to the developing nature of VR technology, the research yielded limited results. Instead, research was shifted to common UX principles used in mobile and tablet development to shape the user's journey within the VR environment.

The user interface was inspired by modern aesthetics with a futuristic and minimalistic style. A style guide was devised showcasing a palette of cool and soothing colors. Taking into consideration that fluorescent lighting prevalent in many university labs tends to be unattractive and unappealing, the aim was to create an environment that would instill a sense of calm and tranquility in students. To enhance the overall experience, futuristic elements such as hexagonal lights and illuminated lab benches were incorporated. This preserved a familiar lab environment with traditional equipment while infusing a contemporary feel.

Building upon the initial wireframe conceived during the ideation phase, the interface was further refined to yield an easy-to-navigate experience for the user. This final wireframe served as a foundation, providing a structured framework for exploration and interaction within the virtual environment.

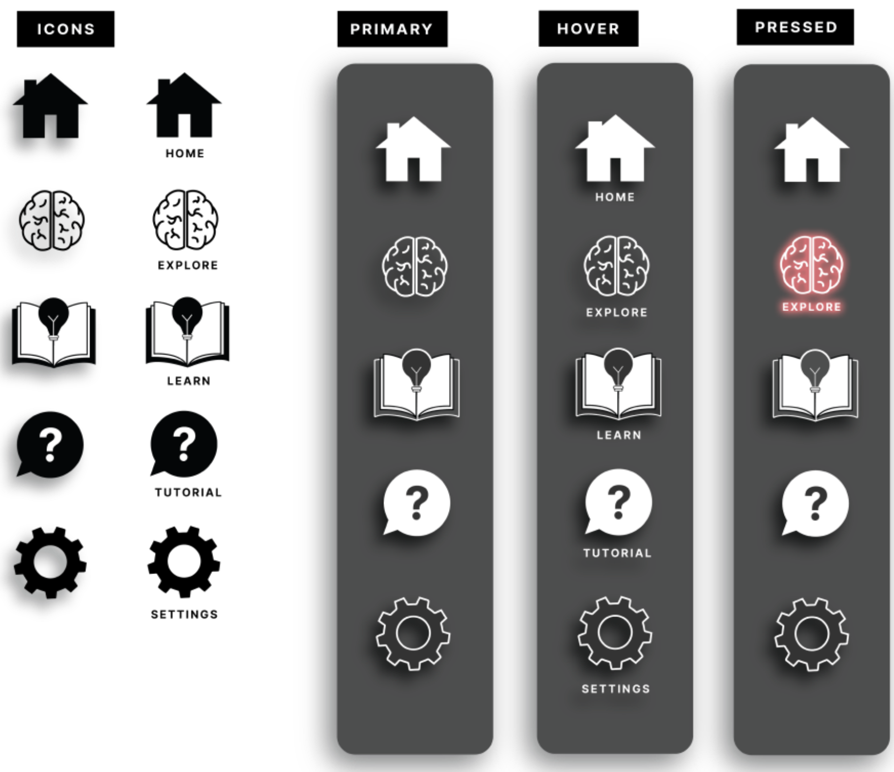


Figure 4. User interface icons illustrated in Procreate and refined in Adobe Illustrator.

D. Construction of the 3D Environment

A comprehensive inventory of assets was created for visual organization. These assets served as a reference during the ideation process were subsequently modeled in Autodesk Maya, adhering closely to the initial sketches. To bring these assets to life, materials and shaders were assigned to the models.

To stimulate a realistic and modern lab environment, lighting was created to be rendered as a mock-up image that would be reconstructed in Unreal Engine.

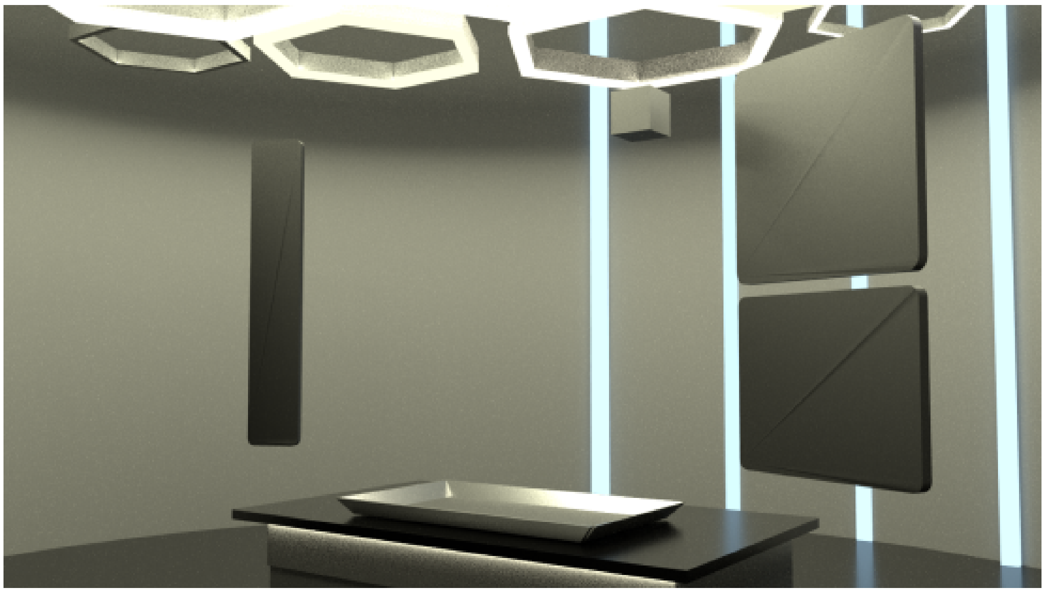


Figure 5. 3D Assets modeled in Autodesk Maya.

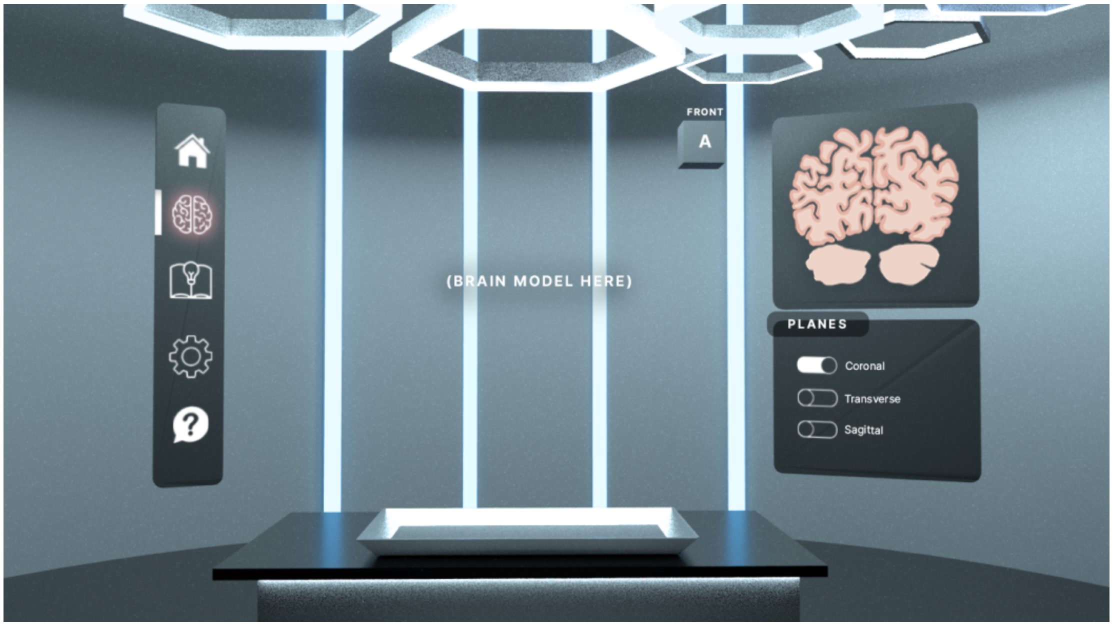


Figure 6. Mock-up of the virtual reality application using Autodesk Maya and Adobe Illustrator.

E. Modeling the Brain

The development of the 3D brain involved a multi-faceted approach, utilizing a range of specialized software programs including 3D Slicer, Mesh Lab, Pixologic Zbrush, Autodesk Maya and Adobe Substance Painter. These programs were vital in achieving the desired level of precision and realism in the final product.

MRI data was obtained from 3D Slicer's sample data library, and brain slices were extracted. The segmentation tool in 3D Slicer was used to compute the MRI images and generate a high-polygon brain model. To optimize the model for sculpting, the high-polygon model was exported from 3D Slicer and processed in the program, Meshlab for decimation to yield a low-polygon model. Decimating a high-polygon model into a low-polygon model is a vital step to prepare a 3D model for a virtual reality environment. Using a low-polygon model makes sculpting more efficient and advantageous by allowing room for storage space and memory for the virtual reality application.

Following the decimation process in Meshlab, the low-polygon model was imported into the sculpting pipeline which included using a Wacom Cintiq Pro Tablet and the Pixologic Zbrush software.

During this step, the model was carefully refined and cleaned. Once the sculpting phase was completed, the model was then brought into Autodesk Maya for the important process of UV-mapping. This process allows for the textures to be mapped and ready for the texturing phase. To add a sense of realism to the model, the model was further imported into Adobe Substance Painter for painting and texturing.

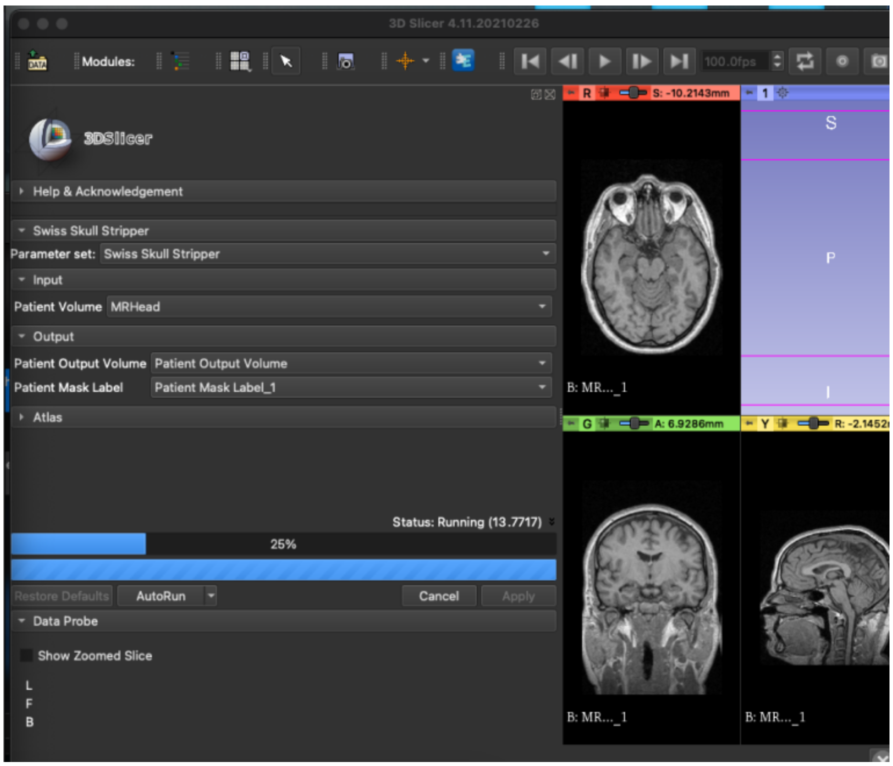


Figure 7. “MRHead” data being used in 3D Slicer.

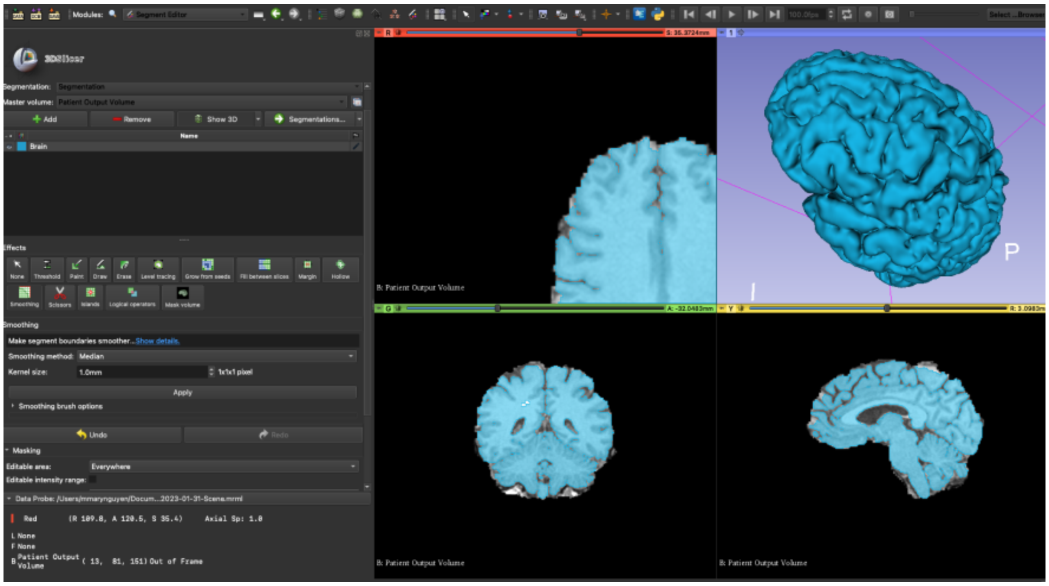


Figure 8. Segmentation module of 3D slicer utilized to create a high-polygon model of the brain.

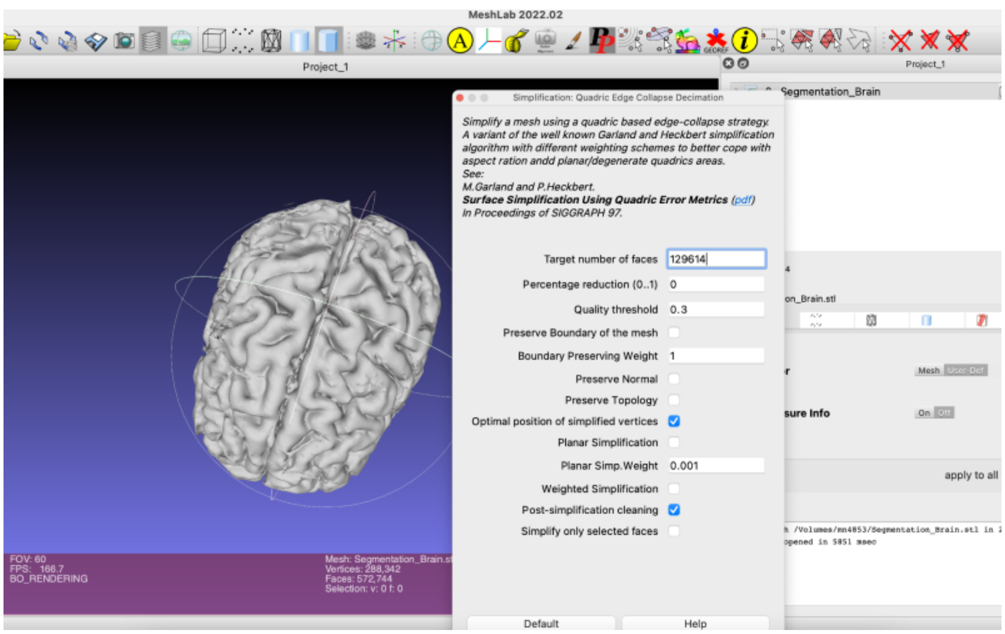


Figure 9. High-polygon 3D Brain Model in Meshlab undergoing Decimation.

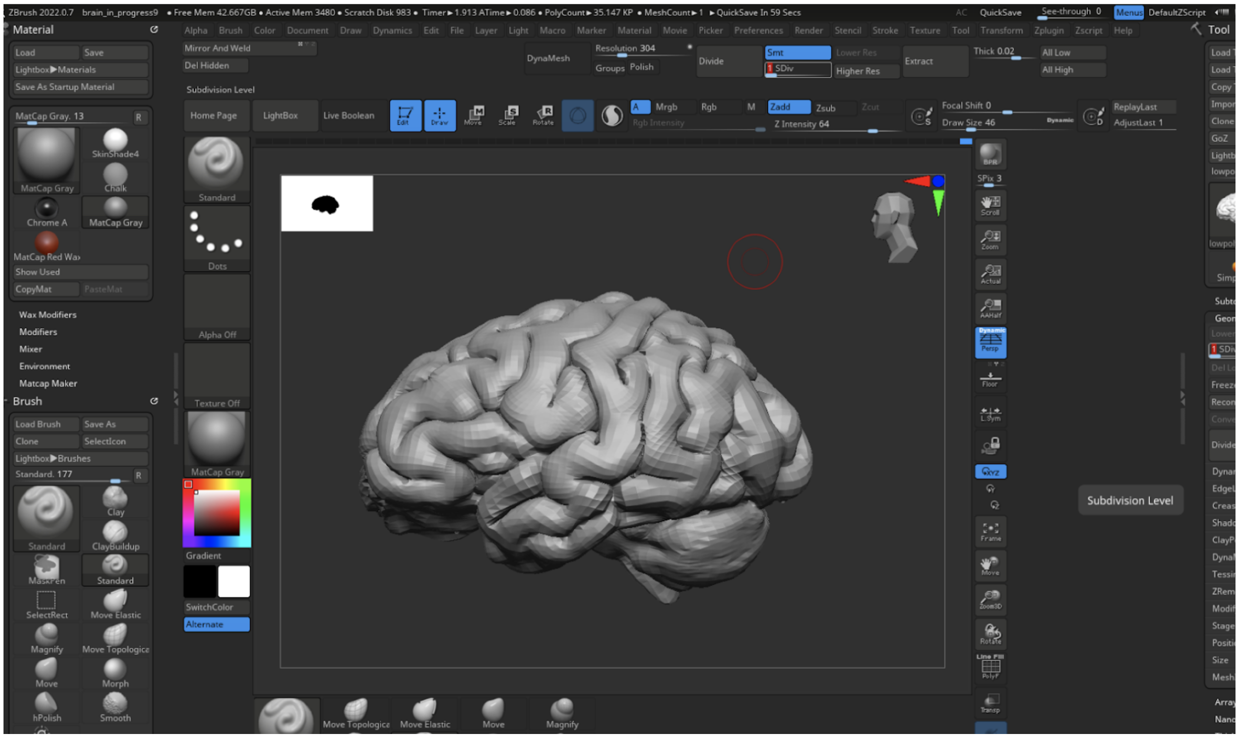


Figure 10. Brain model in Pixologic Zbrush to be sculpted and refined.

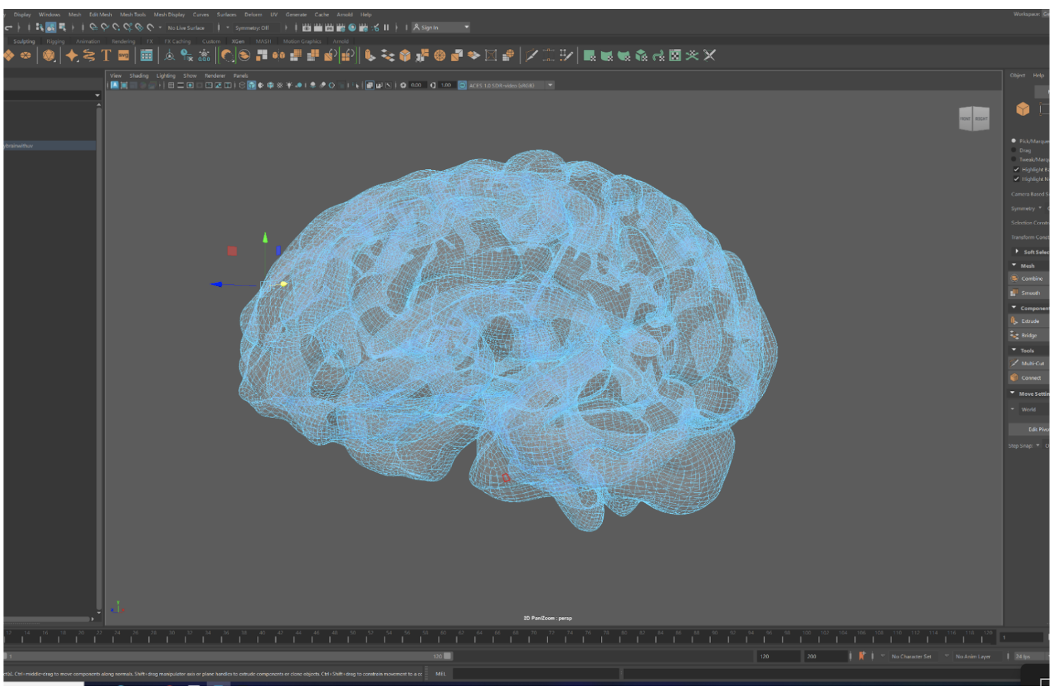


Figure 11. Brain model imported into Autodesk Maya for UV mapping.

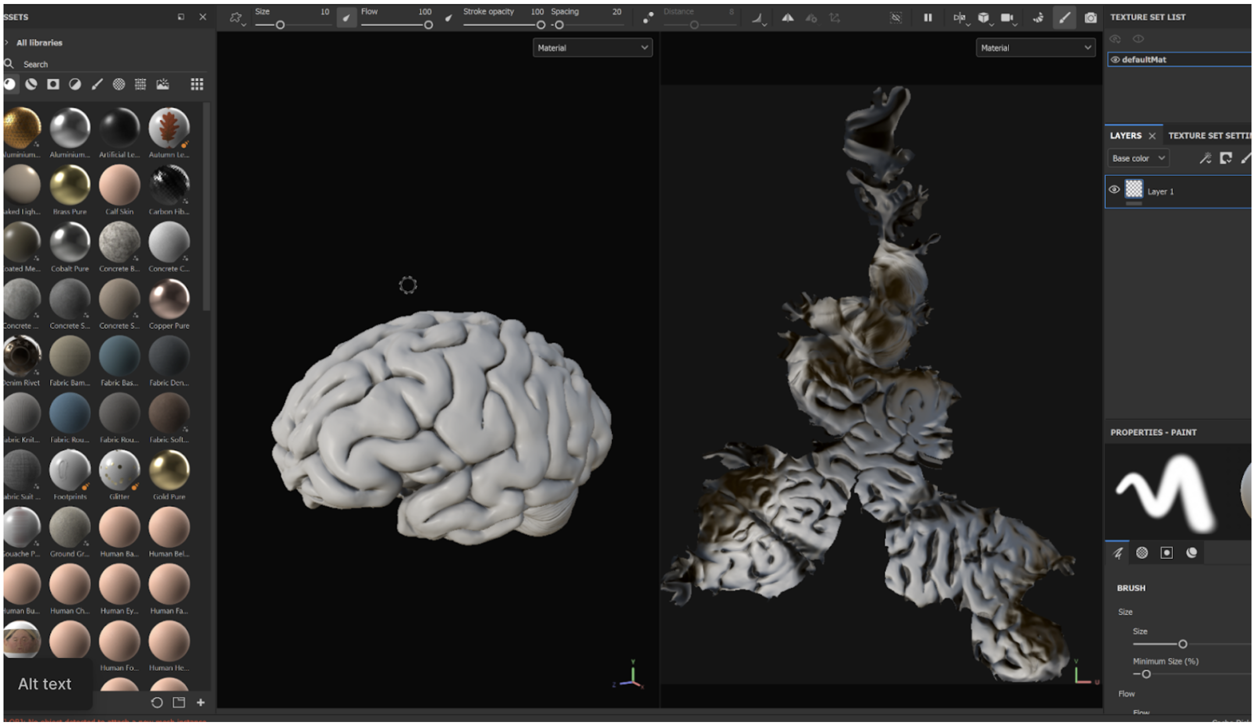


Figure 12. Brain model imported in Adobe Substance Painter.

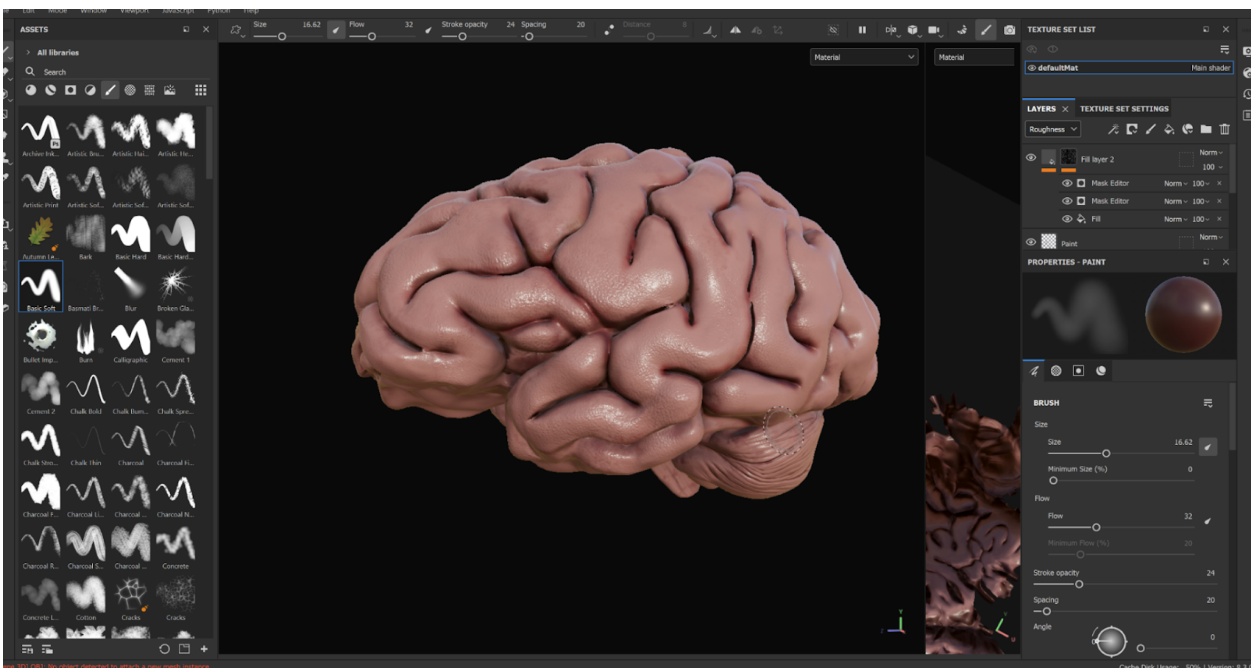
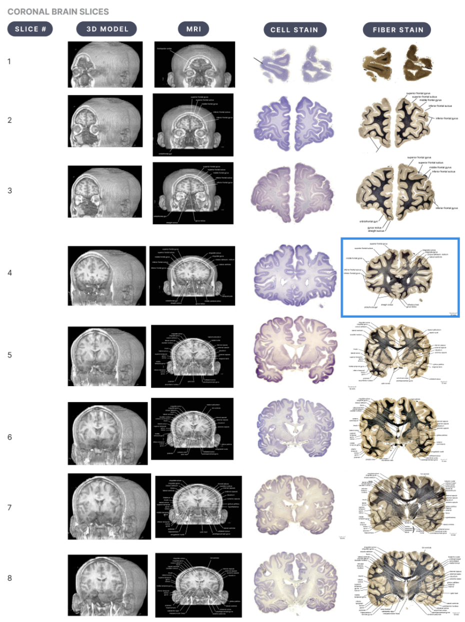


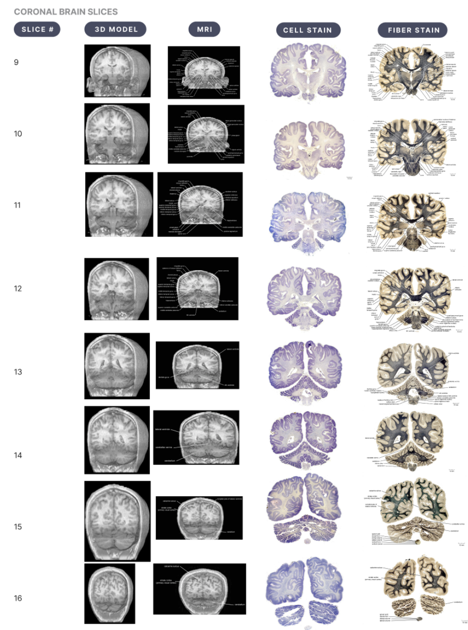
Figure 13. Texturing and painting applied to the 3D model.

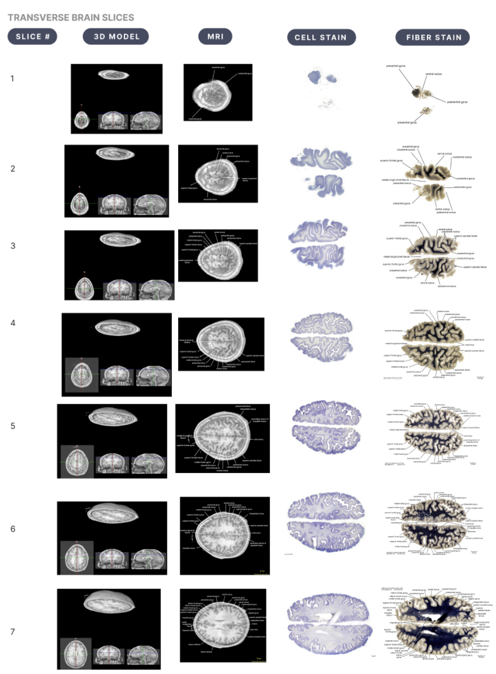
F. Brain Cross-Section Illustration Process

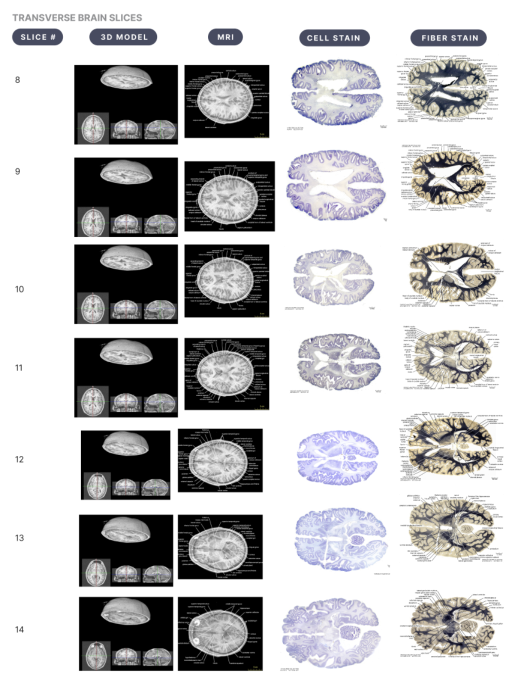
The brain, being highly variable and differing from person to person due to unique arrangement of sulci and gyri, requires one specific dataset to use as the base of the brain for illustrating the cross-sections. To ensure accuracy and clarity, additional references were employed to refine and identify the structures within the slices. The brain cross-section illustration process utilized a variety of sources including multiple textbooks, data from the Brain Biodiversity Bank at Michigan State, and 3D Slicer's "MRHead" dataset that was used in the previous step to construct the 3D model of the brain. These resources were important in helping to fully decipher the intricate structures of the brain in the transverse, coronal and sagittal cross-sections.

Through a meticulous and systematic approach, each reference was carefully organized to ensure that the information obtained from each reference contributed to the overall understanding of the brain and its structures in different planes. Using Procreate, a drawing app, each brain cross-section was individually illustrated using images from the "MRHEAD" dataset and supplementing it with details from other resources. The dataset consisted of low quality images that were challenging to recognize. To overcome this limitation, high-quality histological scans from Michigan State's Brain Biodiversity Bank were employed, enhancing the clarity of the illustrations.


CORONAL BRAIN SLICES
SLICE #
3D MODEL
MRI
CELL STAIN
FIBER STAIN
1
2
3
4
5
6
7
8


CORONAL BRAIN SLICES
SLICE #
3D MODEL
MRI
CELL STAIN
FIBER STAIN
9
10
11
12
13
14
15
16


TRANSVERSE BRAIN SLICES
SLICE #
3D MODEL
MRI
CELL STAIN
FIBER STAIN
1
2
3
4
5
6
7


TRANSVERSE BRAIN SLICES
SLICE #
3D MODEL
MRI
CELL STAIN
FIBER STAIN
8
9
10
11
12
13
14

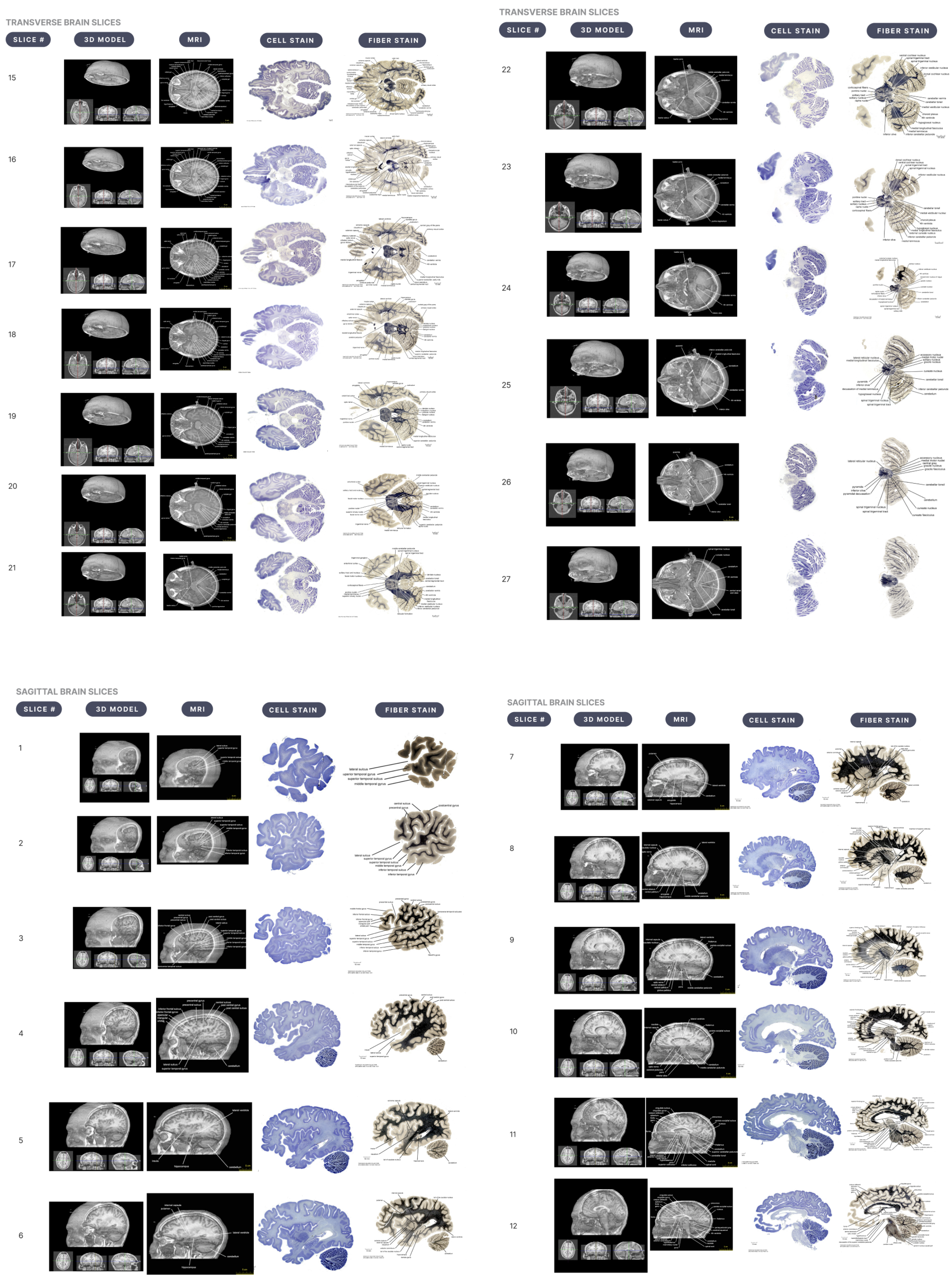


Figure 14. Michigan State's Brain Biodiversity Bank Data organized using Figma.

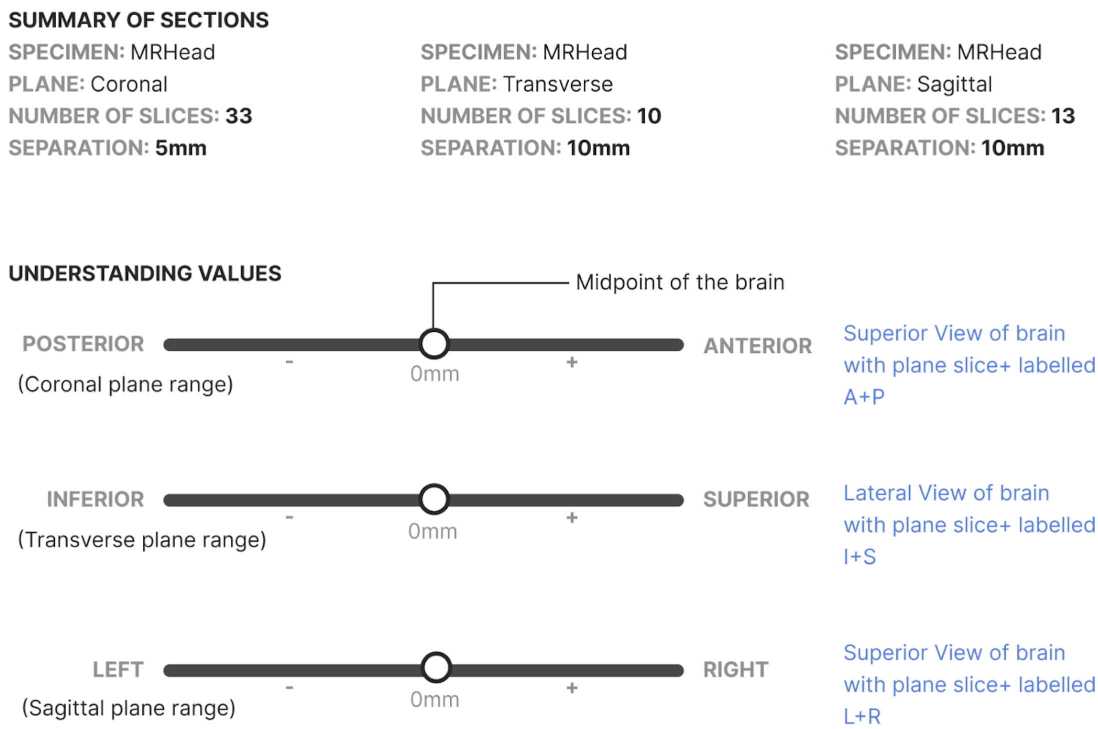
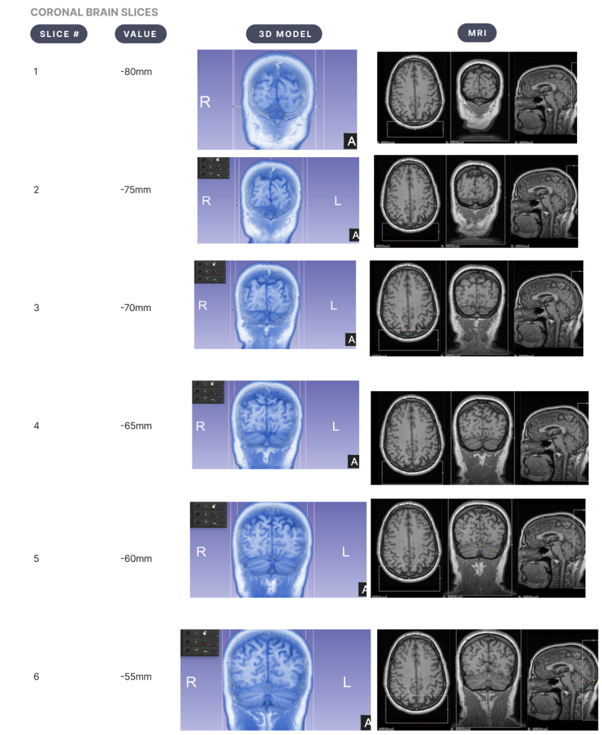


Figure 15. Summary of the organizational structure for 3D Slicer's "MRHead" dataset.


CORONAL BRAIN SLICES
SLICE #
VALUE
3D MODEL
MRI
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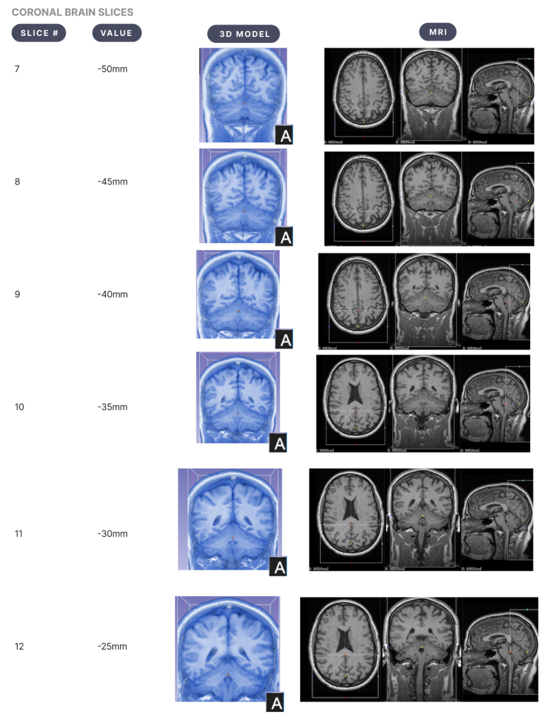
-80mm
2
-75mm
3
-70mm
4
-65mm
5
-60mm
6
-55mm
R
L
A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SLICE #
VALUE
3D MODEL
MRI
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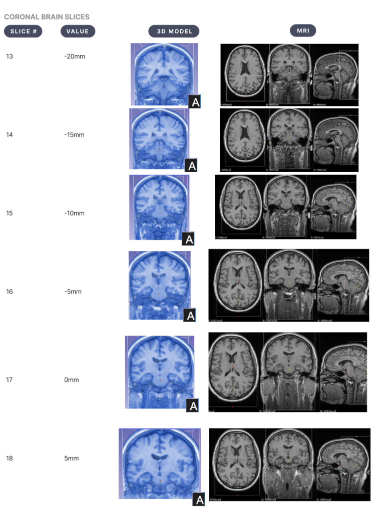
-45mm
9
-40mm
10
-35mm
11
-30mm
12
-25mm
A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SLICE #
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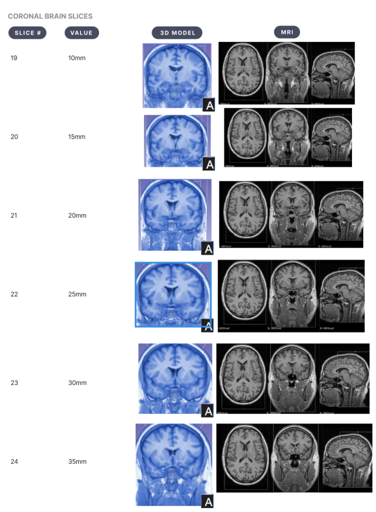
18
5mm
A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3D MODEL
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15mm
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20mm
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25mm
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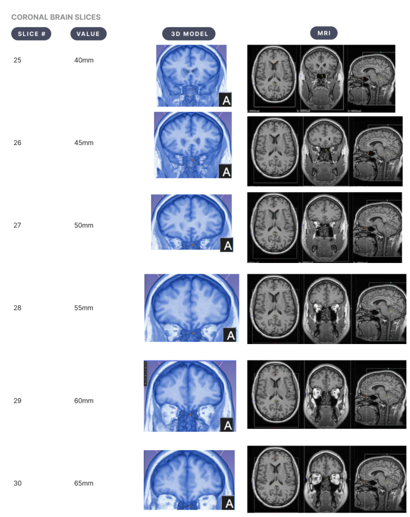
30mm
24
35mm
A


CORONAL BRAIN SLICES
SLICE #
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3D MODEL
MRI
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40mm
26
45mm
27
50mm
28
55mm
29
60mm
30
65mm
A

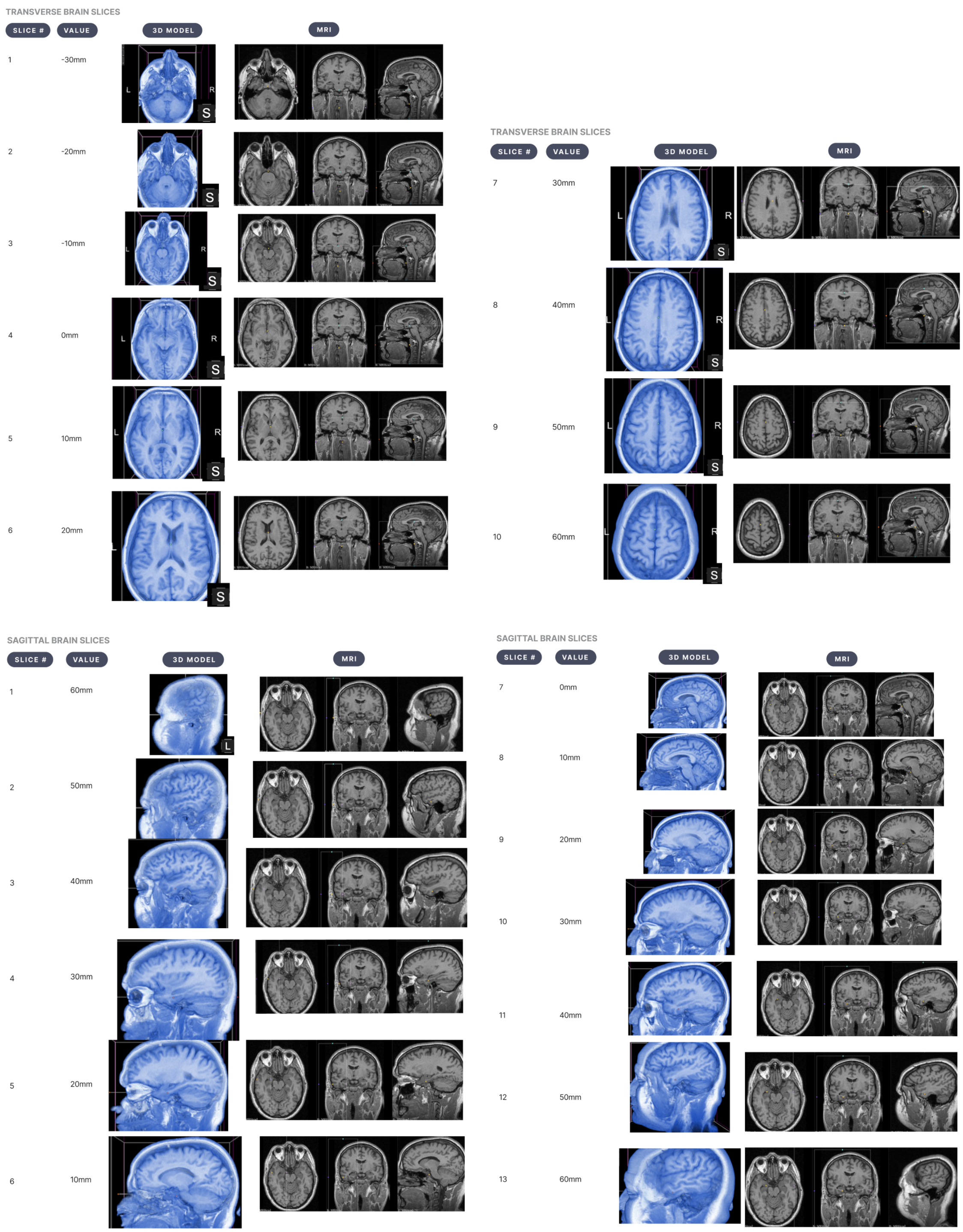

Figure 16. 3D Slicer's MRHead data organized using Figma.

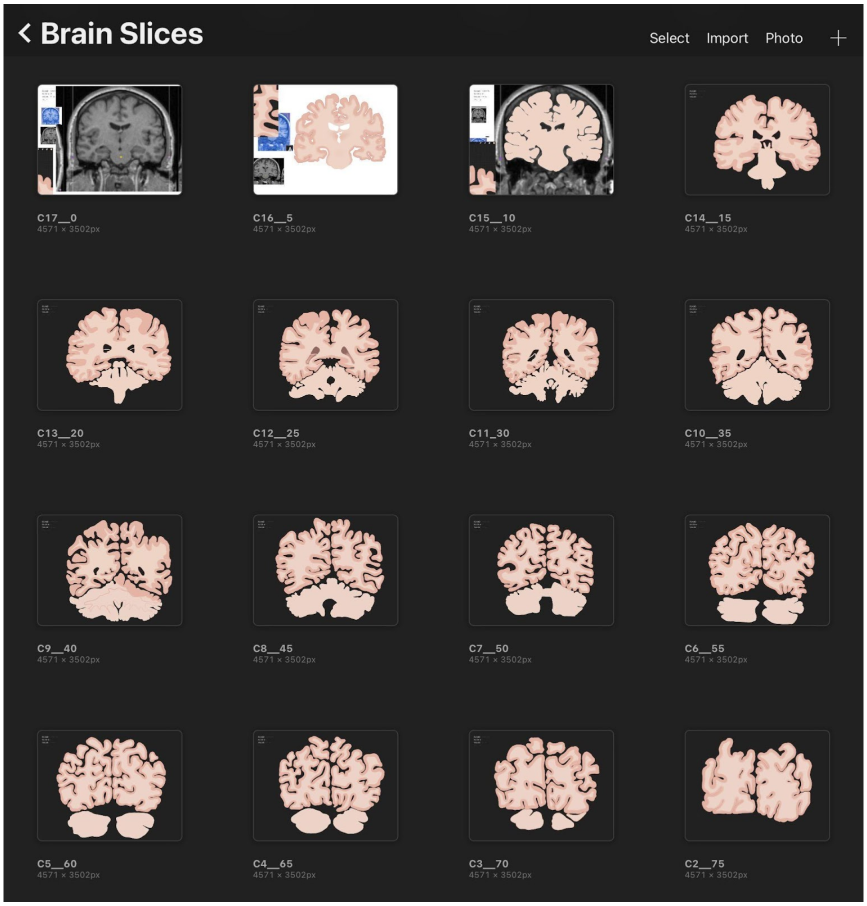

Figure 17. Illustrations of cross-sections on Procreate.

G. Development in Unreal Engine

Once all the assets were modeled and finalized in Autodesk Maya, the next stage involved importing them into Unreal Engine, a game development engine known for its powerful real-time render capabilities. Utilizing Unreal engine's blueprinting visual system, user interface components were incorporated into the scene to enhance the aesthetics and functionality. The blueprint visual system allows coding through a visual programming system. Finally, the 3D model of the brain was imported and made interactive to allow users to engage with it.

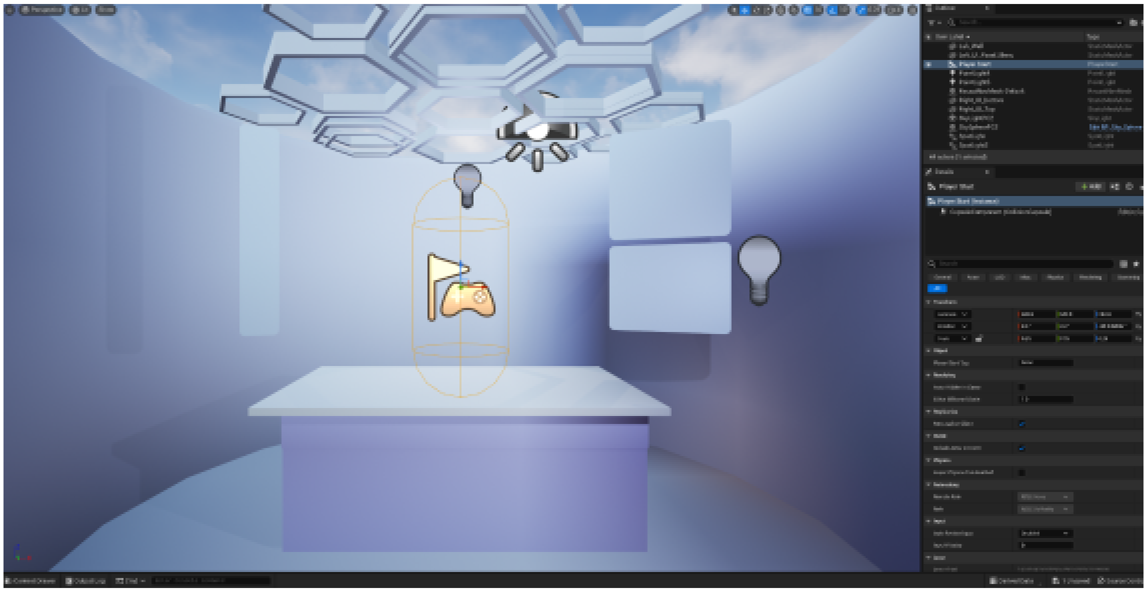

Figure 18. Initial Unreal Engine environment after importing assets.

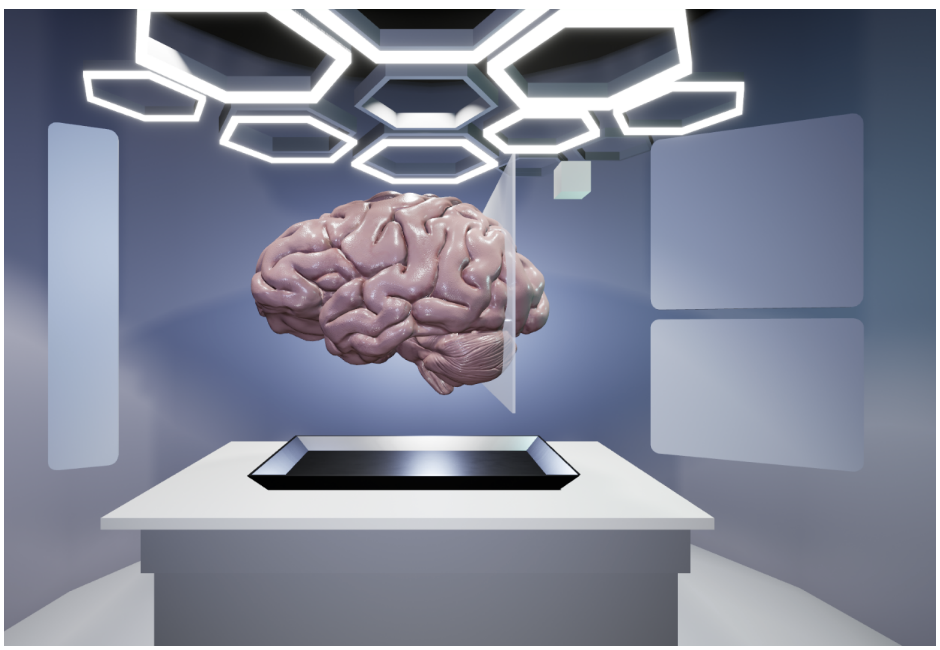

Figure 19. Final Unreal Engine environment after adjusting lighting and adding assets.

V. Conclusion

Although the use of VR in medical education is still in its early stages, it has the potential to revolutionize the way learners and healthcare professionals are trained. This experience can aid learners by allowing them to develop the skills and knowledge they need to be successful and ultimately lead to better patient care and a brighter future for the healthcare industry.

The developed VR application is planned to be used in the Introduction to Cognitive Neuroscience course at the Rochester Institute of Technology. The effectiveness of this tool could be evaluated through a comparison of test scores on specific neuroanatomy-related questions during two semesters: one with the VR application incorporated and one without. These questions require knowledge and reference to the neuroanatomy of vision, visual perception, object recognition and visual attention.

Recognizing the complexity of the brain and its numerous networks and neural pathways, the VR application will be continually expanded to encompass a broader range of topics, going beyond visual neural pathways. This expansion will allow students to delve deeper into various aspects of neuroanatomy, fostering a comprehensive understanding of the brain. By integrating cutting-edge technology like virtual reality, students will have a unique and interactive platform to study neuroanatomy and ultimately foster a deeper grasp of cognitive neuroscience concepts. Through rigorous evaluation and continuous improvement, virtual reality has a potential to play a vital role in education.

VI. Final Illustrations

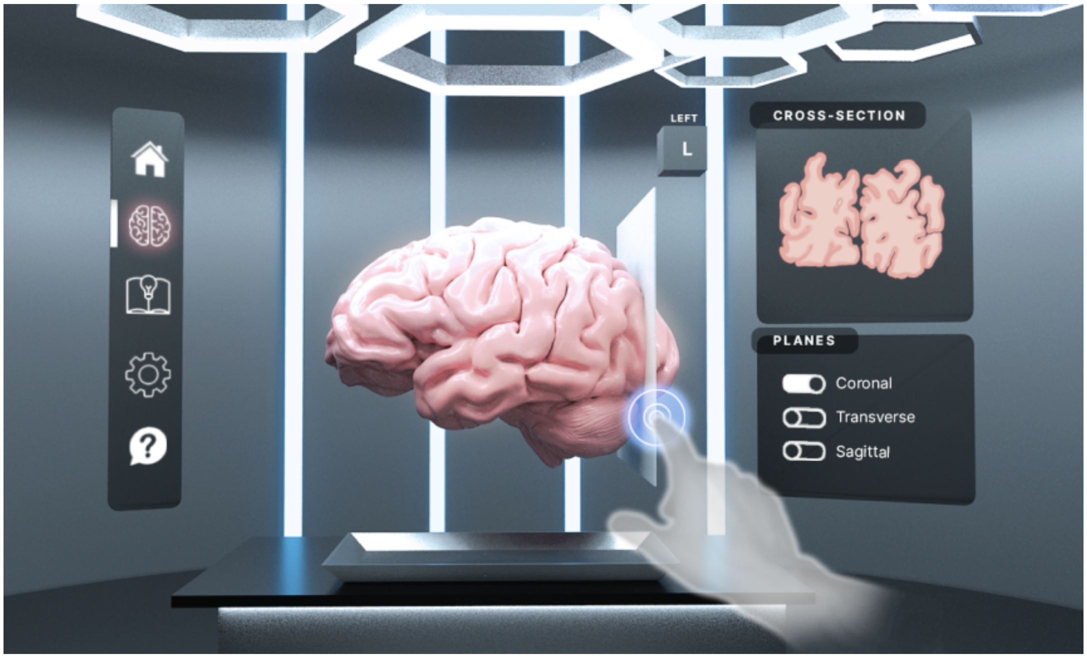

Figure 20. Final mock-up image of the neuroanatomy tool.

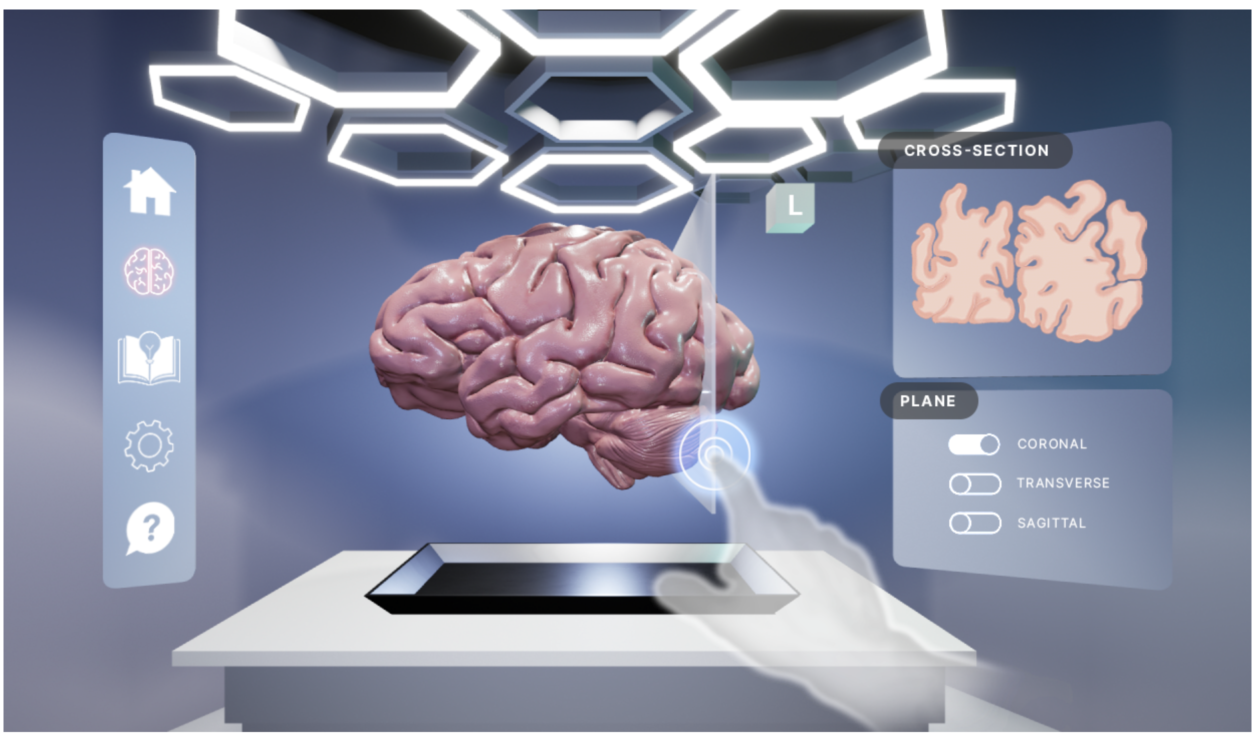

Figure 21. Final environment in Unreal Engine of the neuroanatomy tool.

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