Mobile Augmented Reality Application For the Education of Neurovascular System

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Abstract

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The human brain is a complex organ consisting of intricate vascular networks that supply local regions that control various aspects of our body functions. Understanding the vascular neuroanatomy and the associated territories is essential for diagnosing and treating cerebrovascular disorders such as stroke. Traditional anatomical education relies on 2D illustrations and physical dissections, which often fail to provide a comprehensive understanding of 3D anatomical structures. Augmented reality (AR) and virtual reality (VR) technologies offer immersive 3D visualizations, potentially enabling more effective learning experiences. In this thesis, we present NeuroVase, a tablet-based AR application designed to enhance stroke-related neuroanatomy learning. NeuroVase employs a novel dual-modal setup that leverages physical cue cards as the medium to interact with AR learning content and offer off-line textual learning materials. For the application, we developed a new learning curriculum for the cerebrovascular system with the care of stroke in mind. Users can inspect and explore the brain's vascular territories, understand how blockages in major arteries can lead to specific types of strokes and symptoms, and access key knowledge summaries and 3D anatomical models and MRI. NeuroVase intends to address the limitations of traditional learning methods by offering a more interactive, engaging, and accessible learning tool. The included learning material in NeuroVase can potentially help support time-sensitive treatment decisions and improve prognosis assessment for cerebrovascular conditions, such as stroke. Our platform with modular learning materials was designed with flexibility in mind, making it easy to incorporate additional learning units as needed. Through our user study with 20 participants, the results suggest that NeuroVase could serve as a user-friendly and effective academic and clinical educational tool.

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Chapter 1

Introduction

Neuroanatomy is recognized as one of the toughest topics in medical education because of the intricate and interconnected nature of the central nervous system [10]. With the aging society, the increasing cases of neurological conditions, such as cerebrovascular conditions make the education of neuroanatomy a crucial component in medical training. This is especially important for time-sensitive emergency care, such as treatment decisions for brain stroke, where functional assessment of stroke location in relation to cerebrovascular anatomy is the key. Conventional teaching techniques, such as 2D drawings and cadaver dissections, often struggle to effectively communicate the three-dimensional complexities of neuroanatomical formations. In addition, the functionalities and especially the clinical context of the associated neuroanatomy (e.g., sub-neurosystems for speech) can be difficult to digest with traditional, less-engaging textbook learning. These can lead to sub-standard learning results.

In response to these challenges, innovative educational methods for neuroanatomical learning utilizing 3D digital modeling have been developed. These methods enable the creation of interactive and/or immersive educational experiences that enhance understanding and retention of complex anatomical information. Particularly, virtual reality (VR) and augmented reality (AR) applications provide dynamic 3D visualizations, allowing users to explore and interact with anatomical structures in ways that traditional methods cannot [1]. With the increasing accessibility of AR and VR hardware nowadays, the research and commercial software applications for neuroanatomy are on the rise [22]. However, with most existing reports focusing on more simplistic neuroanatomical knowledge (e.g., general brain lobes), explorations of novel interaction and visualization paradigms are still necessary, especially for the integration of clinical and functional knowledge within neuroanatomical education.

1.1 Motivation of design choices

Traditionally, neuroanatomy education in medical school has relied on using specimens. However, challenges such as increasing student numbers, reduced curriculum time for anatomy, and the scarcity of cadaver resources have necessitated the exploration of alternative teaching methods. AR and VR technologies have emerged as promising solutions, providing immersive, interactive learning experiences without the limitations of physical specimens [15]. While many AR and VR devices have appeared on the market in the past few years, compared with different head-mounted displays, mobile devices, such as tablets and smartphones are still more portable and accessible choices to average users. Considering the aforementioned benefit of AR/VR in anatomical education and the accessibility of devices, mobile AR applications have become a popular choice. These tools not only overcome the logistical challenges associated with traditional learning but also enhance educational accessibility and engagement. Additionally, off-line learning tools, such as cue cards that help summarize key textbook knowledge points still remain as the staple instruments in medical education and clinical training. Given their enduring utility and effectiveness, integrating cue cards with mobile AR applications represents a compelling approach to neuroanatomy education. This integration allows for a flexible, multimodal learning environment that can accommodate diverse learning styles and scenarios. As a result, we would like to explore avenues to combine both tools for neuroanatomical education. More particularly, we focus on cerebrovascular anatomy and related knowledge points on stroke management, which have been overlooked in existing literature and software for AR/VR-based anatomical education. By combining the advanced capabilities of mobile AR with the proven benefits of cue cards, we aim to enhance the comprehension of complex anatomical and related clinical knowledge, ultimately improving the educational outcomes for medical students.

1.2 Contribution

In this thesis, we have developed a mobile AR application, called NeuroVase, for learning neuroanatomy that is related to neurovascular system and stroke. The application leverages physical cue cards to interact with AR educational materials, with three connected learning modules. We hypothesize that mobile AR application with physical cue cards as medium of interaction can be an effective tool for the education of the cerebrovascular system. We aimed to create a positive user experience for the designed system through the proposed user-interaction strategy and dual-modal learning materials. Specifically, our major contributions and features of the application can be described as follows:

- Together with a clinical neurologist specialized in vascular disorders, we developed a new learning curriculum of the general neuroanatomy, cerebrovascular system, and vascular territories for stroke management.
- We proposed a dual-modal system that allows the users to interact with the learning curriculum both through the mobile app and cue cards.
- We designed effective AR user-interaction and visualization strategies that utilize physical cue cards as mediums of interaction.
- The proposed system was thoroughly evaluated through user studies through questionnaires and knowledge quizzes.

1.3 Outline

The structure of the thesis is as follows. We begin with an overview of neuroanatomy and stroke management in Chapter 2. We also present an overview of augmented reality applications in medical education, particularly neuroanatomy, as well as evaluation methods. In Chapter 3, we elaborate on the design and implementation of NeuroVase, the developed interactive augmented reality application for neuroanatomy and stroke education. Further, we report the design and results of the user study that evaluates the usability and effectiveness of the AR system. Finally, in Chapter 4, we conclude the thesis by discussing potential topics of further research.

Chapter 2

Background

In this chapter, we review the use of AR and VR technology in medical education. We begin with an overview of brain stroke management and neuroanatomy. Afterward, we will describe AR and VR and their uses in medical education and previous works. Finally, we will give a short description of the evaluation methods used in this study.

2.1 Stroke and Clinical Management

Stroke is a major contributor to death and disability worldwide. In the past three decades, the global incidence of stroke has risen by 70%, stroke mortality by 43%, and disability-adjusted life years lost due to stroke by 32% [12]. Stroke occurs when the blood supply to part of the brain is interrupted or reduced, preventing brain tissue from getting oxygen and nutrients. This interruption can be due to ischemia, where a blood clot obstructs a vessel, or hemorrhage, where a blood vessel ruptures [13]. Signs of a stroke can range from mild weakness to paralysis or numbness on one side of the face or body. Other signs may include a sudden and severe headache, sudden weakness, trouble seeing, and difficulty speaking or understanding speech [28]. A stroke requires emergency care. Rapid diagnostic imaging, such as computed tomography (CT) or magnetic resonance imaging (MRI) if available, is essential to differentiate between ischemic and hemorrhagic strokes, and to determine the appropriate treatment strategies [30]. In the case of an Ischemic Stroke, the quicker blood flow is restored, the more likely the patient will have better post-treatment outcomes and survival rate. Restoring circulation often involves thrombolytics, medication that dissolves blood clots, but can also involve a minimally invasive catheterization procedure. In the case of hemorrhagic stroke, treatment decision greatly depends on the location and severity of the hemorrhage, and the main aim is to stop the bleeding as early as possible. Surgery is sometimes necessary to relieve pressure within the cranium from accumulated blood. For both types of strokes, clinicians need to make rapid judgement based on the patient's medical scans and good knowledge of the vascular system and supplying functional territories. Finally, rehabilitation is vital to post-acute stroke care, focusing on helping patients regain lost functions and improve their quality of life. This often involves a multidisciplinary approach, including physical, occupational, and speech-language therapy, to meet the patient's specific needs [30].

2.2 Neuroanatomy

Understanding the brain's structural formation and vascular anatomy is fundamental to our AR system, NeuroVase. We designed the learning content for the target mobile application in three separate and inter-connected modules:

Lobar Anatomy Module: The module provides detailed information on the brain's lobes, helping users understand the basic structure and function of each region.

Vascular Anatomy Module: The module guides the user to explore the brain's vascular system, describing the major arteries and their roles in supplying blood to different brain regions.

Vascular Territory Module: The module uses a recently developed 3D digital arterial territory atlas to illustrate the specific territories supplied by each major artery, demonstrating how blockages can lead to different types of strokes and the associated symptoms.

In the following section, we will provide concise overviews of the key neuroanatomical knowledge points with respect to the three learning modules that we developed. The knowledge will offer a background for our technical development and validation.

2.2.1 Lobar Anatomy

To facilitate the understanding of the vascular anatomy and territory modules, basic knowledge on the general brain division is instrumental. Brain comprises white matter, gray matter, and cerebrospinal fluid which flows through the brain's ventricular system and the subarachnoid space. In general, the human brain can be divided into four regions, including cerebral hemisphere, Diencephalon, cerebellum, and brainstem. The illustration of the general human brain anatomy is shown in Fig. 2.1.

- **Cerebral hemispheres**, also known as the cerebrum, represent the largest part of the brain. The cerebrum is composed of four lobes:
  1. **Frontal lobe** is the largest cortical region of the brain, comprising approximately 40% of the cerebral cortex; it is concerned with motor, speech, and executive functions (e.g., planning, problem-solving, inhibitory control, etc.) and emotional modulation.
  2. **Temporal lobe** is located at the bottom of the brain below the lateral fissure. It is concerned with long-term memory formation, formation of visual and verbal memories, emotional regulation, and interpretation of smells and sounds.
  3. **Parietal lobe** forms about 20% of the cerebral cortex and is mainly concerned with spatial computation, body orientation, and visual attention.
  4. **Occipital lobe** occupies the posterior portion of the human brain and is dedicated to visual processing.
- **Diencephalon** is composed of epithalamus, thalamus, and hypothalamus.
- **Cerebellum** is located beneath the posterior cerebrum, dorsal to pons and medulla. It is important in the maintenance of balance, posture, and coordination, as well as timing and strength of contraction of muscles.
- **Brainstem** connects the cerebrum to the spinal cord and the cerebellum. It is composed of:
  1. **Midbrain** (mesencephalon) sits between the forebrain and the pons. It is the home for

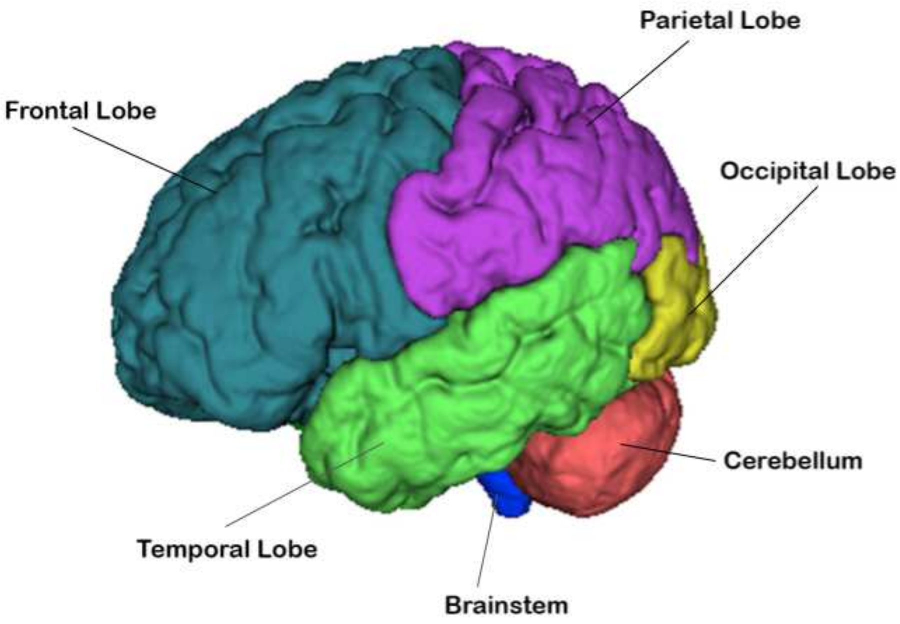


Figure 2.1: Lateral view of the brain

numerous key sensory and motor nuclei, including processing hearing, generating motor commands for the eyes and head, and regulating wakefulness and pain.

(2) **Pons** lies between the medulla and the midbrain and is joined to the cerebellum. It is a significant communication pathway carrying cranial nerves for breathing, hearing, and eye movements.

(3) **Medulla Oblongata** is part of the brainstem between the pons and the spinal cord, which is responsible for maintaining vital bodily functions, such as breathing and heart rate [6][29].

2.2.2 Vascular Anatomy

The arterial vascular system (see Fig. 2.2) supplies the blood flow to provide oxygen and nutrient for different regions of the brain. We summarize the spatial arrangements and supplied regions of the major arterial branches in the brain as below:

- **Middle Cerebral Artery (MCA)** is the largest branch of the internal carotid artery, which supplies blood to the basal ganglia, thalamus, and internal capsule. Cortical branches of the MCA supply blood to the frontal, parietal, and temporal lobes.
- **Circle of Willis** serves as a safety valve function for the brain, allowing blood flow across hemispheres. It is formed by anterior communicating arteries, anterior cerebral arteries, internal carotid arteries, posterior communicating arteries, and posterior cerebral arteries.
- **Internal Carotid Artery (ICA)** arises from common carotid arteries in the neck and can be divided into four general parts according to the area it passes Cervical (neck), Petrous (temporal bone), Cavernous (cavernous sinus), and Supraclinoid (after piercing the dura mater of the meninges).
- **Basilar Artery (BA)** is formed by the union of two vertebral arteries at the ventral pons. It feeds the brainstem and cerebellum while providing distal blood flow to the thalami, medial temporal lobes, and parietal lobes.
- **Anterior Cerebral Artery (ACA)** passes rostrally in the midsagittal plane between hemispheres from the internal carotid artery. It supplies the medial and upper lateral surfaces of the cerebral hemisphere and the upper border of the frontal lobe and parietal lobe.
- **Posterior Cerebral Artery (PCA)** originates at the terminal bifurcation of the basilar artery. It supplies the occipital lobes, inferomedial portions of the temporal lobes, midbrain, thalamus, and deep structures.
- **Vertebral Artery (VA)**: The two vertebral arteries start at the subclavian arteries. They join together at the base of the skull to form the basilar artery, collectively known as the vertebrobasilar system [29][6][31].

2.2.3 Vascular Territories

Different branches of the cerebral arterial system supply their dedicated brain regions with different functions. The knowledge of these “vascular territories” is imperative in time-sensitive treatment decisions of brain stroke and trauma. In vascular territory education, medical drawings of

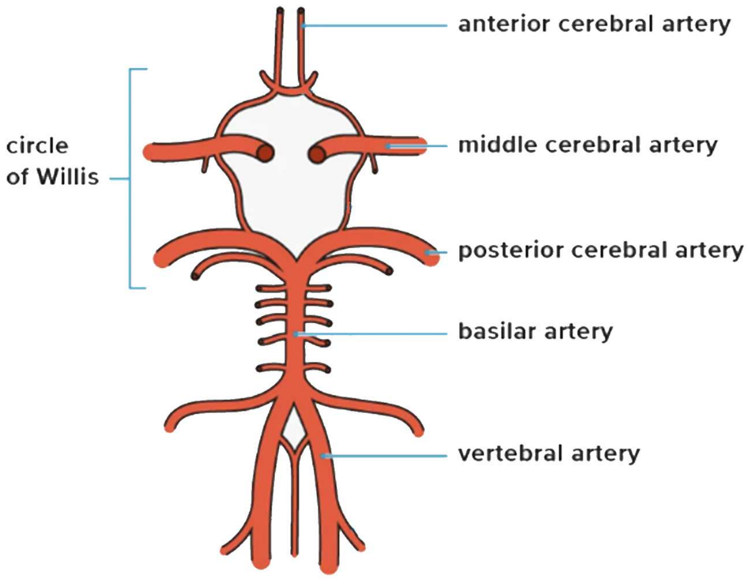


Figure 2.2: Brain major arteries

the representative brain slices in axial views are commonly used. However, these drawings often lack precision and flexibility, especially when the exemplary slices don't match the clinical scans' slice thickness or orientation. With modern neuroimaging techniques, more precise definition in 3D space has become feasible. Recently, Liu et al. [20] developed a publicly available digital arterial territory atlas, providing the clinical and research communities with a digital tool for exploring large-scale data automatically and with high reproducibility. For our AR application, we used the Level 2 version of this atlas that represents the four major arterial territories as shown in Fig. 2.3. With references from the medical textbooks [31][4], we summarize the anatomical composition of the vascular territories and the associated symptoms if stroke lesion occurs in the region below:

- **Anterior Cerebral Artery (ACA) Territory:** This region includes the midline of the frontal lobe, the superior and medial part of the parietal lobe, and the corpus callosum. Strokes in this area are less common due to contralateral flow. Related stroke symptoms include dysarthria, aphasia, unilateral motor weakness, left limb apraxia, and urinary incontinence.

- **Middle Cerebral Artery (MCA) Territory:** Includes the motor, somatosensory, and visual cortices, inferior parietal lobule, inferior frontal gyrus, superior temporal gyrus, nearly all

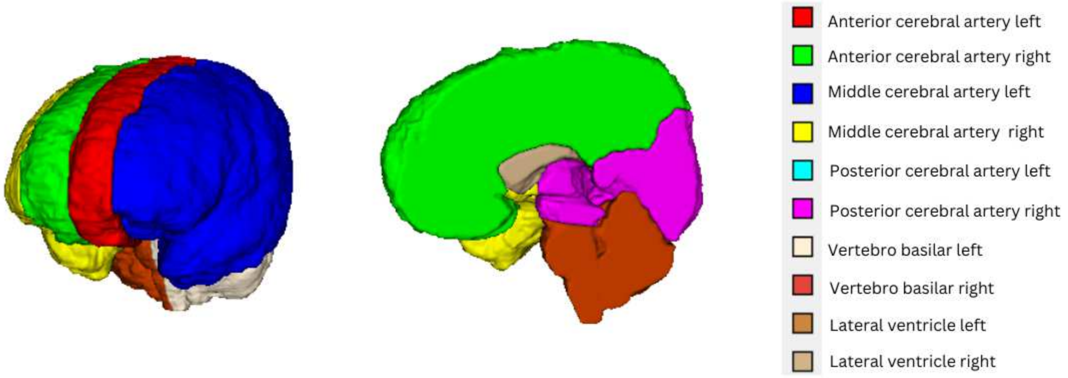


Figure 2.3: 3D rendering of the vascular territory atlas with different color-coding for the corresponding regions.

basal ganglia, and internal capsules. It is the most common site of cerebral stroke. Related stroke symptoms include contralateral hemiparesis (one-sided body weakness), contralateral sensory loss, aphasia, hemianopia (loss of vision in half of the visual field), and hemineglect (reduced awareness of stimuli on one side of space).

- **Posterior Cerebral Artery (PCA) Territory:** Includes the occipital lobe, inferior temporal lobe, medial temporal lobe structures (such as the hippocampus and parahippocampal gyrus), thalamus, and midbrain. Strokes here are rare and have symptoms similar to MCA infarction. Related stroke symptoms include visual loss, visual neglect, somatosensory abnormalities, and cognitive and behavioral dysfunction.
- **Vertebral Basilar Artery (BA) Territory:** Includes the pons, medulla, and cerebellum. Strokes in this region account for approximately 20% of all stroke cases. Related stroke symptoms include dizziness, unilateral limb weakness, dysarthria, headache, vomiting and nausea, gait ataxia, unilateral limb ataxia, dysarthria, and nystagmus (loss of the same half of the visual field in both eyes).

In this section, we concisely summarize the main neuroanatomical structures and the associated stroke symptoms that are relevant to the development of learning materials for our mobile educational AR application, NeuroVase. Note that in the software application, we have provided richer textual learning content than described above to accommodate the need for users with more advanced demand, such as medical school classes.

2.3 Overview of Extended Reality (XR)

Extended Reality (XR) refers to the combination of real and virtual environments, as well as the interactions between humans and machines, produced by computer technology and wearables. XR is an umbrella term that includes various technologies, including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) [5]. Compared with traditional 2D computer monitors, these new technology is especially advantageous in visualizing and interacting data with complex structures and high dimensions. Specifically, **Virtual Reality (VR)** offers a fully immersive 360-degree simulated world where users can interact with the environment and other users within it. In this case, the user has no interaction with the physical world. In contrast, **Augmented Reality (AR)** blends virtual elements like graphics, text, and videos with the real world, enhancing the physical environment with additional knowledge and information. Typically, AR overlays digital elements in the real world, but these elements do not interact with the physical environment. Notably, AR has been shown to significantly influence consumer behavior, with a majority of shoppers preferring stores and apps that utilize AR technology [23]. Finally, **Mixed Reality (MR)**, a hybrid of AR and VR, is the result of blending the physical world with the digital world and allows both to dynamically interact with each other in real-time [24]. Mixed reality places a higher demand on the technical development of the devices as the bridge between VR and AR interactions, and thus can further enhance simulations and training experience without real-world risks [23]. An illustration of the distinctions between VR, AR, and MR is shown in Fig. 2.4.

So far, VR and AR technologies have provided enhanced experience and great benefits for users in industrial design, data science, education, and gaming. They provide a novel experiential learning environment that can revolutionize medical education. Compared to 2D teaching materials (e.g., paper-based and digital textbooks), they would improve spatial awareness and provide unlimited teaching resources that can significantly improve the accessibility of medical education content. The 3D teaching models in these environments are generated from medical data such as

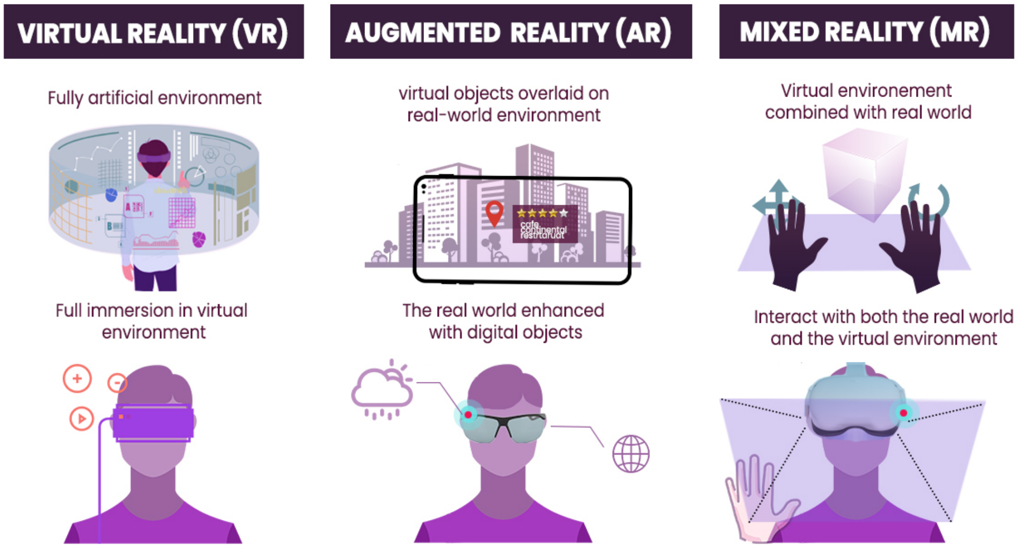


Figure 2.4: Differences between VR, AR, and MR [35]

magnetic resonance imaging (MRI) or computed tomography (CT), allowing limitless dissection and regeneration [38].

Amongst these immersive technologies for learning (AR, VR, MR), AR offers the most affordable and accessible option, as it can be run on the user's smartphone, tablet, laptop, or other camera-enabled device while still providing educational benefits comparable to those of the other modes [25].

2.4 Extended Reality Hardware Devices

Extended reality hardware has significantly evolved in the past decade, incorporating a range of devices designed to enhance user experience by mixing digital information in the real world or completely immersing users in full digital environments. Staple extended hardware includes head-mounted displays (HMDs), including Microsoft HoloLens, Meta Quest headsets, Magic Leap, and the most recent Apple Vision Pro, which project digital content through stereo lenses. Unlike Microsoft Hololens and Magic Leap which leverage see-through lenses for AR views only, Meta Quest and Vision Pro headsets employ front-view cameras that capture the real-world video footage to allow flexible mixing of the digital and physical world at different proportions. In contrast,

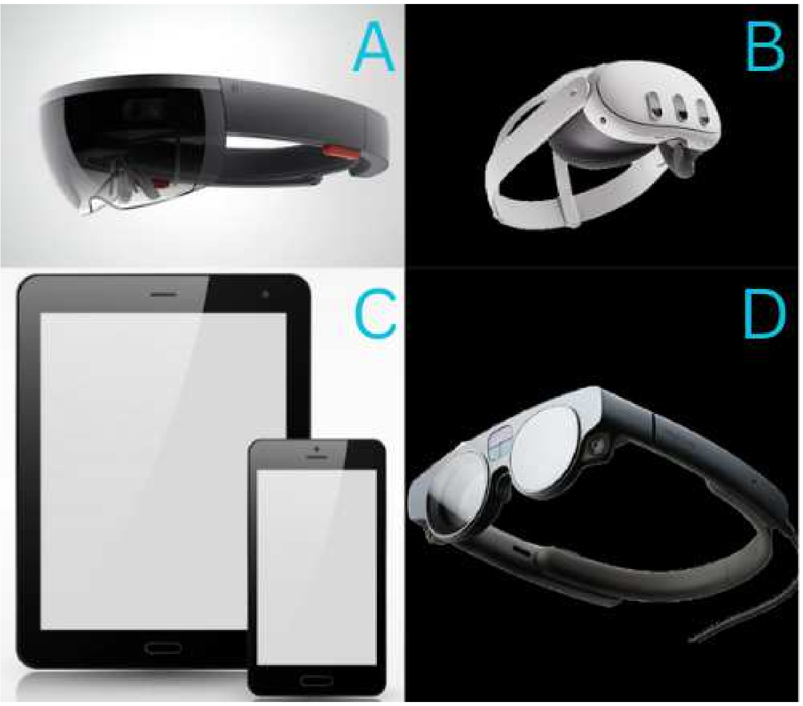


Figure 2.5: Examples of different commercial XR devices: A. Microsoft Hololens, B. Meta Quest 3, C. Tablet and mobile phone, D. Magic leap headset

mobile and tablet devices equipped with cameras and sensors offer more accessible AR experiences through software applications that often utilize marker-based (e.g., QR code or geometric graphics) and/or markerless spatial tracking technologies (e.g., lidar sensor and photogrammetry). To date, these devices have been utilized in various industrial and medical applications, providing intuitive and real-time data visualization and interaction [2] in tasks involving planning, design, training, and analytics. Fig. 2.5 shows the different XR devices.

2.5 VR/AR-facilitated Neuroanatomy Education

Understanding and retaining information in the required learning curriculum can be challenging, particularly for medical students who must learn complex anatomy and the associated physiology. Traditionally, medical learning is based on books and illustrations, and in a limited number of well-resourced educational institutions, students may have the opportunity to dissect actual cadavers. However, paper-based learning materials can lead to misunderstandings, as it is difficult to grasp the intricate 3D relationships between anatomical structures from 2D images. In addition, more medical schools are closing cadaver training courses. As a crucial component of medical learning, neuroanatomy education focuses on the link between anatomical knowledge and practical applications. The increasing number of students, changing curricula, and reduced time allocated to anatomy subjects have prompted the exploration of new teaching methods. Studies showed that students prefer new teaching methods because they are considered to be interactive, engaging, and widely available [38][15].

2.5.1 Neuroanatomy education with virtual reality

The human brain consists of complex and tightly interconnected structures linked by various pathways. When traditional media such as paper and 2D screens convert 3D brain data into 2D slices, it doesn't fully represent the brain's detailed geometry and spatial arrangements, making it challenging to understand its anatomy fully [37]. With the increasing number of VR headsets on the market, a number of studies have been conducted to examine different visualization and interaction paradigms for neuroanatomy education. Stepan et al. [34] compared VR-based 3D brain atlas learning to online textbooks for neuroanatomy. They assessed subjective attributes, such as usefulness, enjoyment, ease of learning, engagement, and presence, as well as test scores at different learning stages. Results showed no difference in learning outcomes, but the VR group found their experience more engaging, enjoyable, useful, and motivational. Later, Lopez et al. [21] examined the benefits of VR-facilitated interactive learning over traditional lectures in neuroanatomy. Their findings indicated that the VR group performed better in identifying brain structures and describing their functional implications during detailed oral examinations using brain MRI with lesions. Another extensive study [33] introduced a VR-based anatomical puzzle game and evaluated it through various user studies, including preliminary feedback, comparison with physical puzzles, collaborative learning, and remote learning. The subjective evaluations (ease of use, fun, usefulness, and presence) were positive, but there was no clear improvement in knowledge acquisition and retention. Gloy et al. [11] also assessed learning efficiency and knowledge retention by comparing response times and accuracy in post-intervention quizzes between immersive anatomical atlas users and standard atlas textbook users. Their results showed that the VR-based approach demonstrated better learning efficiency and retention. Most recently, Hellum et al. [14] designed an innovative virtual reality platform, The SONIA VR system, to enhance the learning and exploration of functional brain systems and networks. It integrates neural pathway exploration with learning module design, focusing on neuroanatomy and connectivity learning. SONIA employs innovative visualization and interaction strategies, such as multi-scale brain models and systematic color-coding, to enhance usability and user experience. Unlike previous systems that focus on simple anatomical visualization, SONIA offers an immersive and user-friendly environment enriched with detailed narratives of brain sub-systems and effective user-interaction strategies. Validated through user studies, the system showed positive impacts in user engagement and motivation, with a mean SUS score of 79.8 out of 100. Its customizable open-access design allows for flexible learning content, paving the way for future advancements in VR-based medical education.

2.5.2 Neuroanatomical education with augmented reality

Since AR can be used on a user's own smartphone, tablet, laptop, or other camera-enabled devices, it provides an affordable and accessible solution that helps with learning. Moro et al. [25] developed an AR application for stroke education and compared it to a traditional text-based pamphlet. Using a tablet-based AR app with interactive 3D brain models and a pamphlet with identical content, 101 participants were divided into two groups. While both groups showed improved post-test scores with no significant difference, the survey indicated that AR learning was superior in explaining stroke concepts. However, the study noted that the young, tech-savvy participants might limit the generalizability of the results to older adults, the primary audience for stroke education. In another study, Moro et al. [26] compared various computer-based learning methods—specifically tablet-based AR, headset-based AR, and virtual reality—and their effectiveness in teaching anatomy. They found that these three methods were not significantly different in teaching anatomy. In terms of medical training with anatomical education, Mu et al. [27] developed a novel augmented reality simulator for percutaneous renal access (PCA) and evaluated its validity and efficacy as a teaching tool. The cost-effective, flexible, and customizable AR training simulator was shown to be effective for acquiring PCA skills. The simulator's simple setup allows training at home, protecting patients from unnecessary harm and providing a stress-free environment for repetitive practice. However, its performance is sensitive to lighting conditions, requiring moderately bright and diffused lighting for the best experience. In terms of mobile AR applications for neuroanatomy education, Henssen et al. [15] developed GreyMapp and compared it to traditional learning with illustrations of anatomical cross-sections. Results showed that while GreyMapp reduced cognitive load and increased motivation, the control group using cross-sections had higher post-test scores. Other metrics like pre-test scores, spatial ability, and motivation did not significantly differ between groups. The study concluded that while AR can supplement traditional methods and specimens, it may not fully replace them. However, 3D visualization techniques can be a promising and valuable addition to anatomy education [39]. Using AR-goggles, Ille et al. [17] proposed to utilize virtual white matter fiber dissection based on tractographies obtained from diffusion MRIs to learn different key neural pathways for neurosurgical treatment. Their findings suggest that the AR system was beneficial and has promising potential for both educational and clinical use [17].

2.6 Trend in tablet-based AR education

With technological advancements, tablets witnessed significant growth between 2014 and 2020. Mobile devices have become the most commonly preferred delivery device for AR technology due to their convenience, high interactivity, and standalone operation. Tablet devices integrate the advantages of mobile phones and computers with larger screens and higher performance, support various input formats, and provide high-quality visualizations, leading them to become the most dominant computing devices. Since 2016, wearable devices (e.g., portable AR goggles) have also been used in AR-based instruction, bringing higher levels of engagement and immersion. These wearable technologies' applications can potentially support situated, embodied learning in real-world contexts [40]. In a systematic review, Zhang et al. [40] concluded that no significant differences among various devices for AR-based education exist, suggesting that the most suitable device can be chosen based on cost constraints. This confirms the benefit of using mobile AR for neuroanatomy education due to its affordability and accessibility.

2.7 Evaluation Methods

The assessment of VR/AR-based medical education systems is multi-facated and often needs to be evaluated by multiple metrics to sufficiently evaluate the usability and attitude of users on visualization and interaction strategies, educational outcomes, and so on.

2.7.1 System Usability Scale (SUS)

The System Usability Scale (SUS) is a widely used tool for evaluating the usability of systems and interfaces, developed by John Brooke in 1986 [3]. SUS is a software evaluation test consisting of 10 different questions, each with five response options ranging from “strongly disagree” to “strongly agree” (on the Likert-scale of 1-5). Questions are related to system usability and complexity. A SUS score ranges from 0 to 100, with higher scores indicating better usability. Based on SUS evaluation scoring, any system with a score higher than 68 is indicated as a good system in terms of ease of use for users. SUS is valued for its simplicity, reliability, and ease of implementation across different systems and contexts [32].

2.7.2 Study knowledge tests

Knowledge test scores are commonly used in educational research and practice to evaluate students’ understanding of specific content before and after teaching. These tests measure the knowledge acquisition of participants by comparing their performance on standardized questions. Prestudy tests are given before teaching to assess the initial level of knowledge, while post-study tests are administered after teaching to evaluate what has been learned. The difference in scores can indicate how effective the teaching method was. The validity of these tests depends on well-designed questions and statistical analysis to ensure that they accurately measure the intended knowledge gains [16].

2.7.3 Customized metrics for AR educational software

In addition to standardized usability and knowledge test scores, evaluating educational tools often includes additional metrics to allow a more nuanced understanding of the effectiveness of the developed system. While many metrics have been proposed as Likert-scale questionnaires, the factors of immersiveness and joy have been shown to correlate with positive educational outcomes of the VR/AR-based educational systems. Specifically, immersiveness refers to the extent to which a learning environment can engage and captivate students, making them feel as though they are truly part of the educational experience. High levels of immersion can lead to better engagement and deeper learning. This can be measured through user feedback, behavioral engagement indicators, and qualitative interviews [19][36]. Joy, or the enjoyment factor, is another critical metric, particularly in educational contexts. It assesses users' emotional responses to the learning process. Enjoyable learning experiences can enhance motivation and increase the likelihood of knowledge retention. Methods to evaluate joy include surveys with Likert-scale questions, focus groups, and observational studies. Both immersiveness and joy contribute significantly to the overall effectiveness and user acceptance of educational tools, offering a more comprehensive understanding of their impact [36][8].

2.7.4 Freeform feedback

In addition to the semi-quantitative and quantitative evaluation tools mentioned earlier, freeform feedback from the users that helps justify their scores for the evaluation tools is also crucial. By providing further comments and suggestions on the software system's positive and negative points, developers can better understand the existing software and user experience design, and thus pinpoint areas for improvement.

2.8 Moving forward

As can be seen from the related research, augmented reality and 3D visualization techniques can be a potential and valuable addition to anatomy education. Based on the information gained in this chapter, we offer an AR tablet-based application for neuroanatomy education. We describe NeuroVase in the next chapter.

Chapter 3

NeuroVase: A mobile augmented reality application for the education of the neurovascular system

A version of this chapter will be submitted to the **Anatomical Sciences Education** Journal.

3.1 Introduction

The education of neuroanatomy and the associated brain physiology is an important component for the investigation and clinical care of neurological disorders, but it is often complicated by the intricate spatial configuration of the anatomical structures and complex narratives [10]. This is especially true for time-sensitive practices, such as treatment decisions for brain stroke, where correct functional assessment of stroke location and extent in relation to cerebrovascular anatomy based on clinical scans (e.g., CT) is key. Conventional teaching techniques, such as 2D drawings and cadaver dissections, often struggle to effectively communicate the three-dimensional complexities of neuroanatomical formations in an engaging manner. With increasing accessibility for the hardware and advantage in volumetric data visualization and interaction, virtual and augmented reality (VR/AR) have been adopted for neuroanatomy education [1].

To date, a number of software systems and studies have been reported to explore the effectiveness of different paradigms for AR- and VR-based neuroanatomy education. For VR systems, Stepan et al. [34] compared 3D brain atlas learning in VR to online textbooks. While there was no difference in learning outcomes with knowledge quizzes, the VR group found their experience more engaging and motivational. Later, Lopez et al. [21] found that VR-facilitated interactive learning helped participants perform better in identifying brain structures and describing their functions compared to traditional lectures. Additionally, Souza et al. [33] introduced a VR-based anatomical puzzle game, which received positive subjective evaluations, but failed to show a clear improvement in knowledge acquisition and retention. In contrast, Gloy et al. [11] demonstrated that VR-based approaches could enhance learning efficiency and retention compared to standard atlas textbooks. Most recently, Hellum et al. [14] designed a novel VR system that enhances neuroanatomy education by offering immersive and customizable visualization of complex 3D brain structures and neural pathways.

In AR applications, Moro et al. [25] developed a tablet-based AR application to display general brain lobes and textural learning content for stroke education, which proved more effective than traditional pamphlets in explaining stroke concepts. Furthermore, Moro et al. [26] also compared tablet-based AR, headset-based AR, and VR in teaching anatomy, and showed no significant differences in learning effectiveness among these methods. Recently, Henssen et al. [15] developed a mobile AR application for neuroanatomy education, which demonstrated reduced cognitive load and increased motivation for learning, but did not outperform traditional methods in learning outcomes. Finally, with AR goggles, Ille et al. [17] proposed virtual white matter fiber dissection to teach key neural pathways, showing promising potential for both educational and clinical use. These previous studies have showcased positive impacts of AR/VR on neuroanatomy education. However, most often utilize relatively simple 3D brain models with a sole focus on brain lobes and overlook the related physiological knowledge. As a crucial component of neuroanatomy, the vascular system and territories with strong clinical significance has not been explored. Furthermore, while studies [15] suggested complementary roles of AR and paper-based learning, few explored paradigms to integrate them. For example, paper-based learning tools, such as cue cards still remain as the staple instruments in medical education and clinical training. Given their enduring utility and effectiveness, integrating cue cards with mobile AR applications represents a compelling approach to neuroanatomy education.

In this study, we developed and validated a novel tablet-based AR application, named NeuroVase, which provides specialized content on vascular anatomy and stroke education, areas significantly overlooked by existing AR/VR applications. The application's tablet-based platform leverages the widespread accessibility and familiarity of tablet devices, enhancing user-friendliness and broad accessibility. Compared with existing reports, our work has three major contributions. First, we developed a new learning curriculum of the general neuroanatomy, cerebrovascular system, and vascular territories for stroke management. Second, we proposed a dual-modal system that allows the users to interact with the learning curriculum both through the mobile app and cue cards. This dual-purpose use of cue cards allows for more flexible and engaging learning experiences. Third, we designed effective AR user-interaction and visualization strategies that utilize physical cue cards as mediums of interaction. We validated the usability and effectiveness of the proposed system through a user study with semi-quantitative questionnaires and knowledge quizzes.

3.2 Methods and Materials

For our proposed NeuroVase system, we employed physical cue cards to enable the interaction with the digital content shown on the tablet, and to provide key knowledge point review in an off-line mode. The digital learning materials are comprised of both textual content and the associated 3D digital models built based on a healthy subject's MRI scan. We describe different components of the proposed system in the following sections.

3.2.1 Learning material development

We developed a learning curriculum in collaboration with a neurologist that is specialized in the care of cerebrovascular disorders that comprises of three inter-connected modules, including general anatomy of the brain lobes, cerebral arterial system, and vascular territories. In the brain lobar module, we introduce the spatial arrangement and basic functions of the general brain divisions, including the frontal, temporal, parietal, and occipital lobes, brainstem (midbrain, pons, and medulla oblongata), and cerebellum. This relevant material serves as the necessary foundation to better understand the learning materials of the vascular anatomy and territories. This is especially instrumental for users, who are new to the topic. For the cerebral arterial system, we introduce the spatial arrangement, formation, and supplying regions of the main arterial branches, including the inferior carotid, anterior cerebral, middle cerebral, posterior cerebral, vertebral, and basilar arteries, as well as the Circle of Willis. Finally, the arterial territory module that was developed based on the work of Liu et al. [20] presents a 3D definition of these vascular territories based on a large stroke patient cohort. In this learning module, for each of the anterior cerebral, middle cerebral, posterior cerebral, and vertebral basilar territories, we describe the associated functional brain regions, frequency of stroke occurrence, and related stroke symptoms. To accommodate different characteristics of the media, we developed more detailed learning content for the mobile device while keeping a concise summary of the key knowledge points for the cue cards.

3.2.2 Data Processing and Digital Model Construction

To accompany each learning module for enhanced anatomical understanding, we constructed the required virtual brain models with segmentation of 3T MRI scans of a healthy subject's brain and publicly available brain atlases. For the learning module on general anatomy of the brain lobes, we extracted the anatomical structures mentioned in the previous section from the BCI-DNI brain atlas by Joshi et al. [18], which includes high-resolution manually labeled brain parcellations from a healthy adult female's MRI scan. For the vascular anatomy and territories, we built the digital model from a healthy individual's anatomy. Upon informed consent, the subject was scanned with T1-weighted MRI (1x1x1 mm^3 resolution) and time-of-flight (TOF) MR angiography (MRA, 0.47x0.47x0.70 mm^3 resolution) using a GE Discovery MR750 MRI scanner. The brain surface and arteries were extracted from the MRIs with the BEaST algorithm [7] and Frangi vesselness filter [9], respectively. In addition, we also conducted further manual refinement of the arterial labels and segmented the main vessel branches using ITK-SNAP (http://itksnap.org). For the vascular territories, we non-linearly registered the arterial territory atlas by Liu et al. [20] to the individual's MRI. This atlas was constructed based on lesion distributions in 1,298 patients with acute stroke.

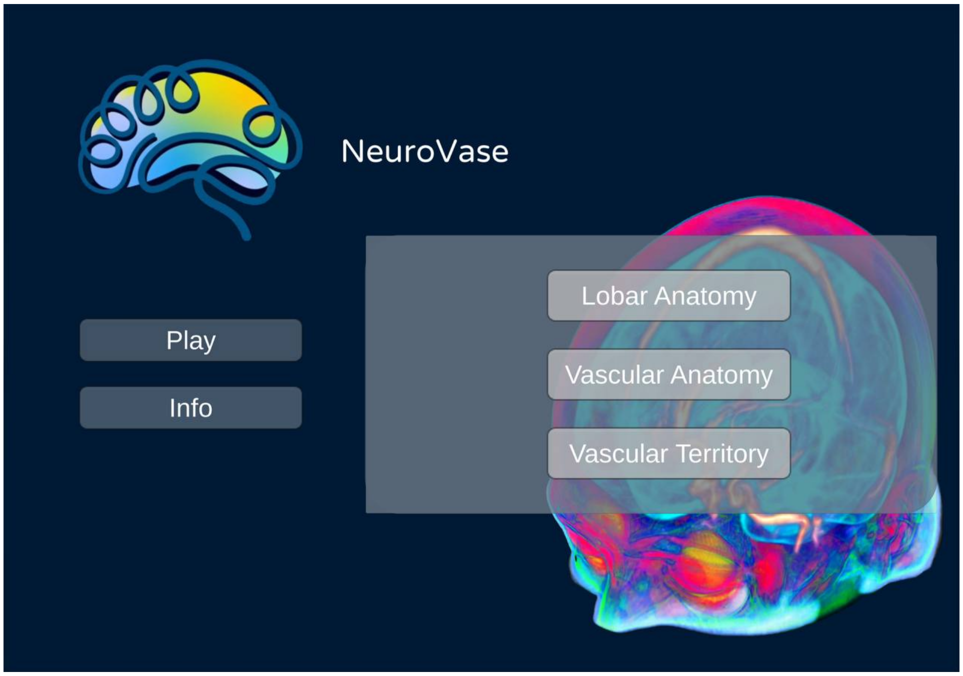


Figure 3.1: NeuroVase application menu page

As the atlas has two levels of granularity, we used Level-2 of the subdivisions with four major territories. All segmentations were saved as polygon mesh models in .obj formats for the rendering in the NeuroVase application.

3.2.3 Software Implementation

The Unity 3D game engine version 2023.1.16f1 was used for our software application development, and C# was used for the scripts to communicate with the Unity engine. The Vuforia Engine asset was used to implement the AR-based data display. This asset allows for spatial tracking of a printed image target with a video camera by extracting its natural features and then augmenting the virtual content above it. We designed the fronts of the cue cards to be our image targets and provided sufficient geometric features for the Vuforia Engine to detect them. Furthermore, an “Easy Volume Renderer” asset (https://github.com/mlavik1/UnityVolumeRendering) was used to import the MRI scan into Unity for additional data visualization. A demonstration of NeuroVase’s menu interface and system setup are shown in Figs. 3.1 and 3.2, respectively.

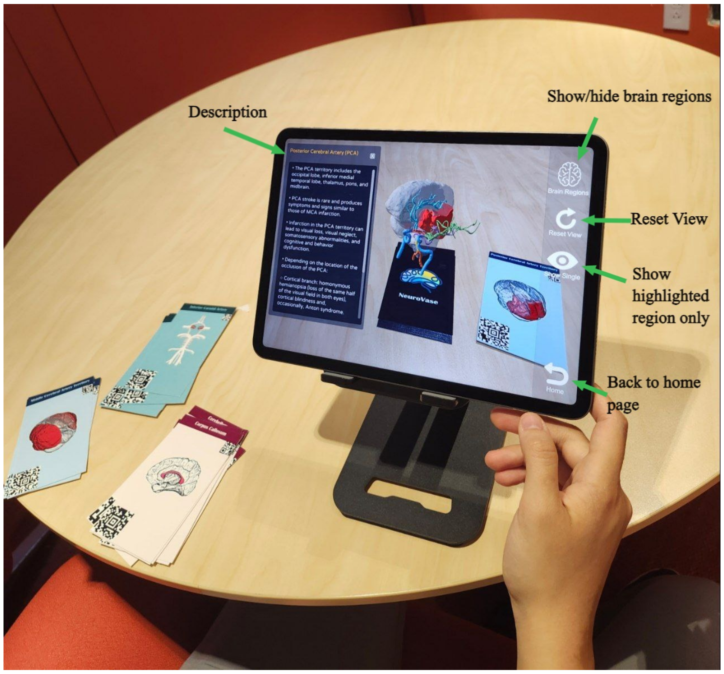


Figure 3.2: A demonstration of NeuroVase, an interactive augmented reality application for neuroanatomy and stroke education. In the demonstration, the user is using the application to learn the Vascular Territory module.

3.2.4 Cue Card Design

The cue cards were made with a common Taro card size (2.75in x 4.75in) and consist of one master card to position the anatomical model spatially in the AR view and a series of trigger cards to update the medical knowledge point and related visual content for the AR display, as well as to serve as an off-line review tool. Besides the master card, we designed three sets of cards with their respective color-coding: nine cards for the brain lobes, seven for the vascular system, and four for the arterial territories. A few samples of the trigger cards are shown in Fig. 3.4. Specifically, each trigger card contains the concise summary of a knowledge point (e.g., an arterial branch) on the back and the related anatomical illustration on the front, which the Vuforia Engine relies on to update the AR content. As Vuforia requires sufficient details (number of features and edges) and enough local contrast for detection, in addition to the anatomical illustration, we also placed two QR codes on the top right and bottom left corners of each card to enhance the robustness for optical detection. An illustration of the card design and the detected keypoints by Vuforia is shown in Fig.

3.3.

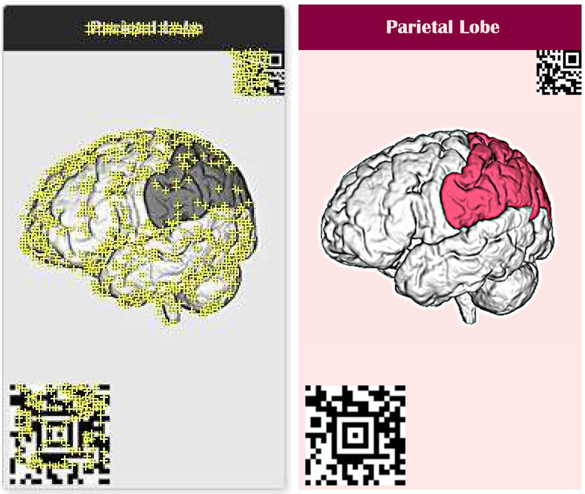
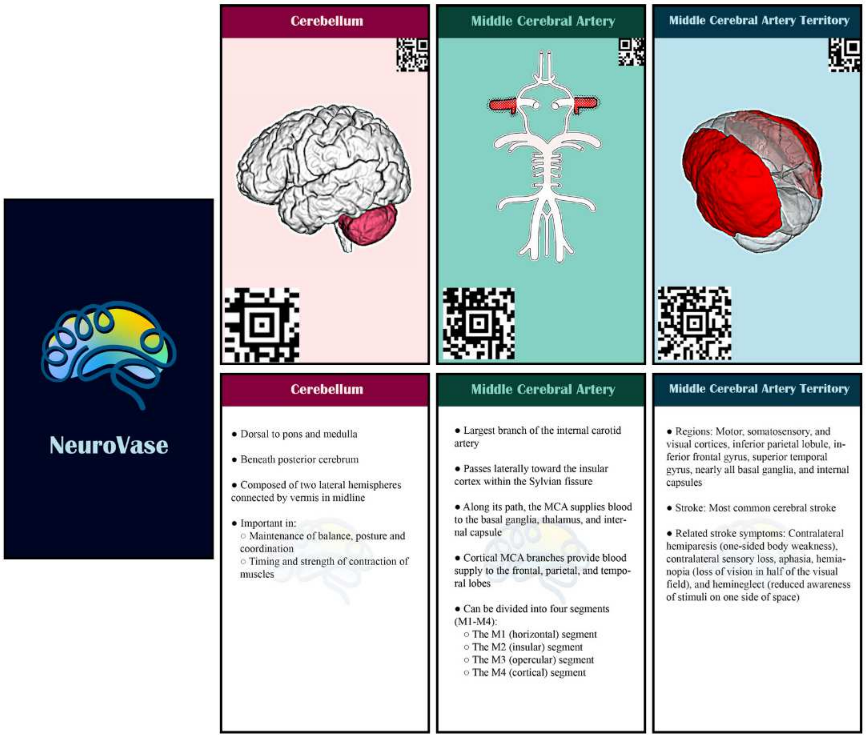


Figure 3.3: Demonstration of image feature detection by Vuforia. Left: keypoints extracted by Vuforia; Right: original card design for the learning material of parietal lobe.

3.2.5 User Interface Design

We designed easy-to-use interface features to deliver the learning content. First, at the main menu page, as shown in Fig. 3.1, we display tabs for all three learning modules. This modular design allows future addition of educational content and flexibility in learning content selection. Once entering a learning module by clicking on the tab, we designed graphic user interfaces to accommodate the needs of each. For the three learning modules, Figs. 3.5, 3.6, and 3.7 demonstrate the setups when the main card is placed in the camera view and how the scene changes when a trigger card is added, by highlighting the relevant anatomical structures and displaying descriptions of the anatomy. Here, each module's interface includes a 'Home' button to return to the main page and a 'Reset View' button to restore the anatomical model to its original size, position, and color after user manipulation. The text box for learning material is positioned to the left of the menu to avoid blocking the view of the anatomical model, making information easy to access without distraction. We also designed features that are unique to each module. Specifically, in the lobar anatomy module, a 'Sulci and Fissures' button further triggers the visualization of these anatomical features, which define the boundaries for the lobes. In the vascular anatomy and territories modules, a 'Brain Surface' button allows users to toggle the visibility of the brain's surface to better view



Cerebellum

- Dorsal to pons and medulla
- Beneath posterior cerebrum
- Composed of two lateral hemispheres connected by vermis in midline
- Important in:
  - Maintenance of balance, posture and coordination
  - Timing and strength of contraction of muscles

Middle Cerebral Artery

- Largest branch of the internal carotid artery
- Passes laterally toward the insular cortex within the Sylvian fissure
- Along its path, the MCA supplies blood to the basal ganglia, thalamus, and internal capsule
- Cortical MCA branches provide blood supply to the frontal, parietal, and temporal lobes
- Can be divided into four segments (M1-M4):
  - The M1 (horizontal) segment
  - The M2 (insular) segment
  - The M3 (opercular) segment
  - The M4 (cortical) segment

Middle Cerebral Artery Territory

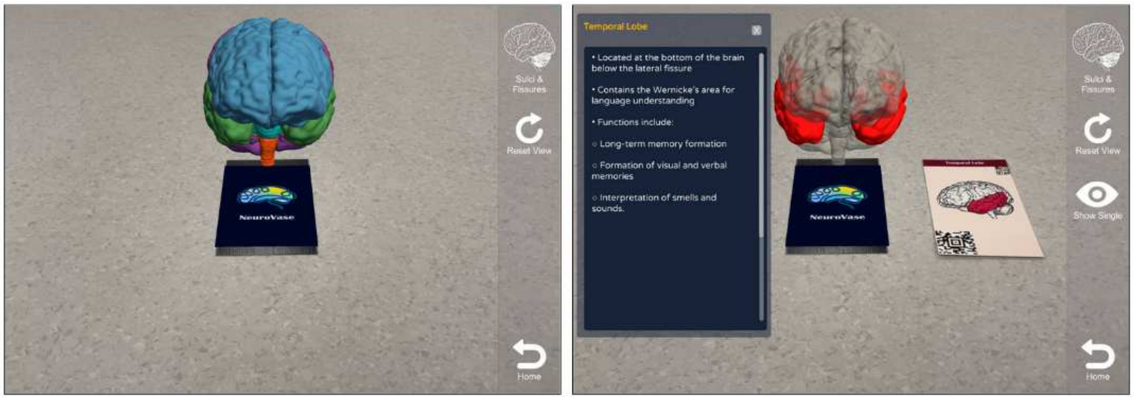
- Regions: Motor, somatosensory, and visual cortices, inferior parietal lobule, inferior frontal gyrus, superior temporal gyrus, nearly all basal ganglia, and internal capsules
- Stroke: Most common cerebral stroke
- Related stroke symptoms: Contralateral hemiparesis (one-sided body weakness), contralateral sensory loss, aphasia, hemianopia (loss of vision in half of the visual field), and hemineglect (reduced awareness of stimuli on one side of space)

Figure 3.4: Main card and an example of a card and its back for each phase

vascular structures or territorial divisions as needed. To further enhance spatial understanding, the vascular module further includes an additional ‘Show MRI’ button that displays MRI slices in Coronal, Axial, and Sagittal views, as shown in Fig. 3.8 with the aid of three sliders. This feature highlights the integration of medical imaging techniques with anatomical learning, enhancing the educational experience by linking 3D models with real diagnostic imaging.

3.2.6 User Interaction Paradigms

Physical cue cards offer an intuitive and tangible way to interact with virtual models, potentially enhancing user engagement and learning. While the main card is used to set the position for the virtual anatomical model, when a user places a trigger card beside the main card in the camera view, the AR view will be updated for the content that the trigger card represents. The user can scale and shift the anatomical model with two-finger pinch/unpinch and swipe, respectively, and rotate the model with one-finger swipe. The ability to manipulate and inspect the digital model



Temporal Lobe

- Located at the bottom of the brain below the lateral fissure
- Contains the Wernicke's area for language understanding
- Functions include:
  - Long-term memory formation
  - Formation of visual and verbal memories
  - Interpretation of smells and sounds.

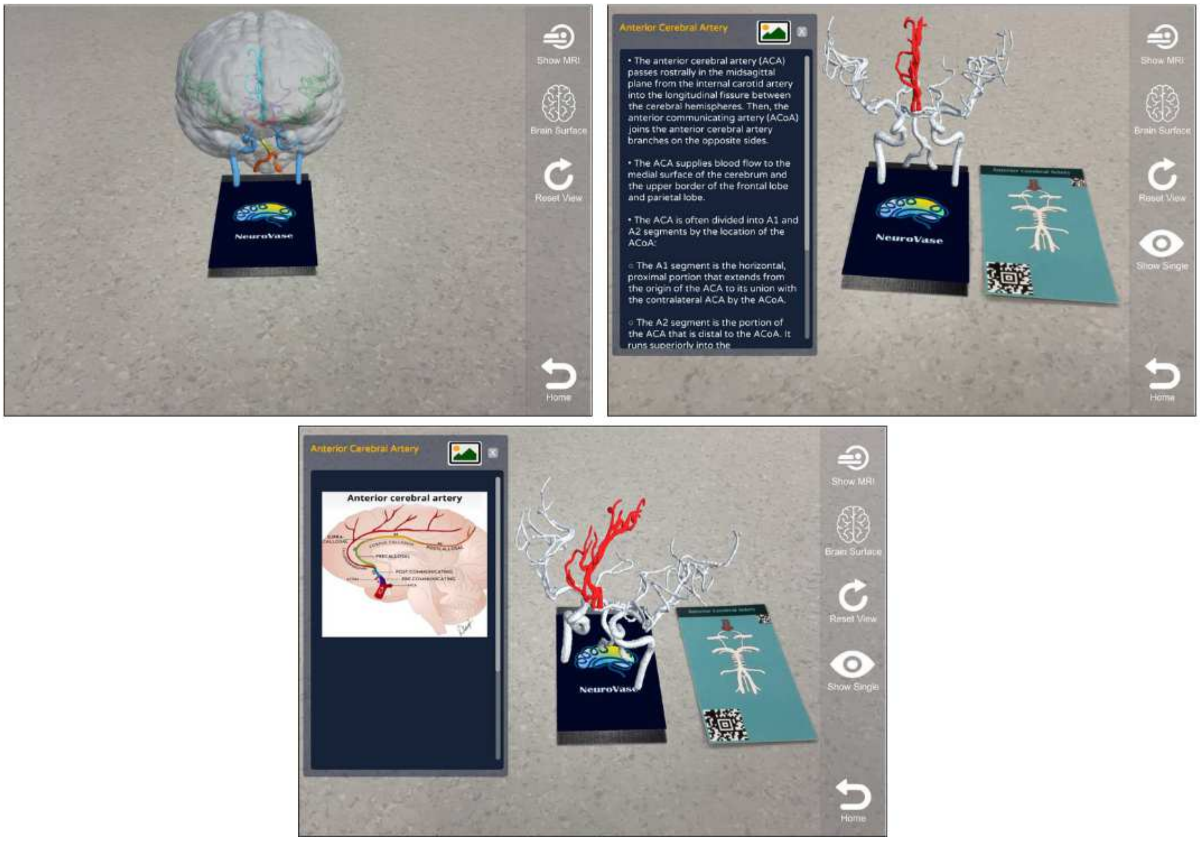
Figure 3.5: Lobar anatomy learning interface before and after activation by a trigger card

from different angles can help enhance the spatial learning of the target anatomical structures. In addition to finger-gesture-based manipulation, the user can also achieve translation and rotation of the anatomical model but changing the positioning of the master card. Note that for our system, we purposefully disable the function to use finger-tapping to select the anatomy of interest to view the relevant learning content. This is because, in our pilot study, we noticed that finger-gesture-based spatial transformation often switch the learning content by accident when such function was allowed. In addition, to help guide the learning curriculum in the desirable order (lobar anatomy, arterial system, and vascular territories), the cue cards can only be used for the designated learning module, and those for other modules cannot trigger any interface updates.

3.3 User Study Design and System Validation

To evaluate the usability and effectiveness of the proposed NeuroVase system, we conducted a user study. Upon informed consent, approved by Concordia University's Ethics, we recruited a total of 20 participants (9 females and 11 males, age = 29.0 ± 4.3 yo) who are STEM undergraduate and graduate students with limited knowledge on cerebrovascular anatomy and territories.

For the user study, each participant used the system on a 10.9-inch iPad to complete the designed learning modules in 20$\sim$30 min. The sequential description of the user study is as follows:
First, each participant received an introduction to explain the overall study procedure and a short tutorial on the proposed NeuroVase system. Then, they were asked to complete a pre-study quiz



Anterior Cerebral Artery

- The anterior cerebral artery (ACA) passes rostrally in the midsagittal plane from the internal carotid artery into the longitudinal fissure between the cerebral hemispheres. Then, the anterior communicating artery (ACoA) joins the anterior cerebral artery branches on the opposite sides.

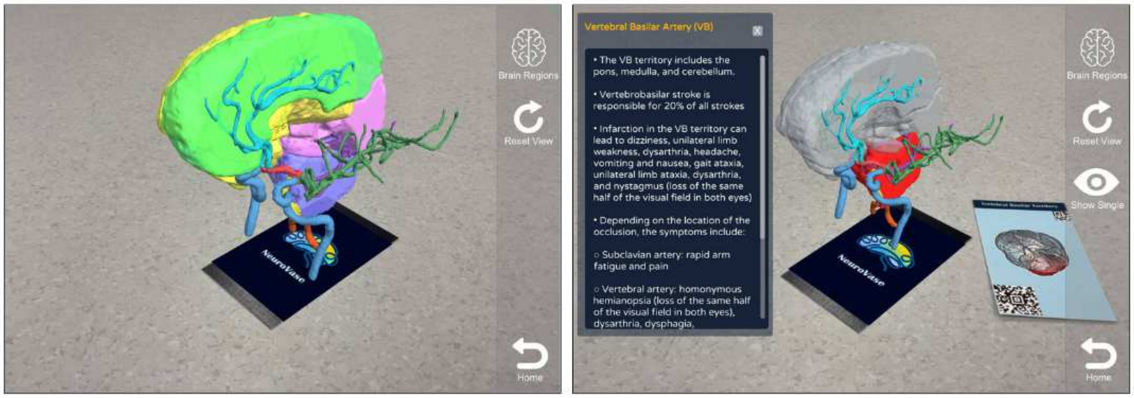
- The ACA supplies blood flow to the medial surface of the cerebrum and the upper border of the frontal lobe and parietal lobe.

- The ACA is often divided into A1 and A2 segments by the location of the ACoA:

  ○ The A1 segment is the horizontal, proximal portion that extends from the origin of the ACA to its union with the contralateral ACA by the ACoA.

  ○ The A2 segment is the portion of the ACA that is distal to the ACoA. It runs superiorly into the

Figure 3.6: Vascular anatomy learning interface before and after activation by a trigger card. The bottom image shows detailed sub-branches of the vascular in the 2D illustration after pressing the image icon.



Vertebral Basilar Artery (VB)

- The VB territory includes the pons, medulla, and cerebellum.

- Vertebrobasilar stroke is responsible for 20% of all strokes

- Infarction in the VB territory can lead to dizziness, unilateral limb weakness, dysarthria, headache, vomiting and nausea, gait ataxia, unilateral limb ataxia, dysarthria, and nystagmus (loss of the same half of the visual field in both eyes)

- Depending on the location of the occlusion, the symptoms include:

  ○ Subclavian artery: rapid arm fatigue and pain

  ○ Vertebral artery: homonymous hemianopsia (loss of the same half of the visual field in both eyes), dysarthria, dysphagia,

Figure 3.7: Vascular territorial learning interface before and after activation by a trigger card

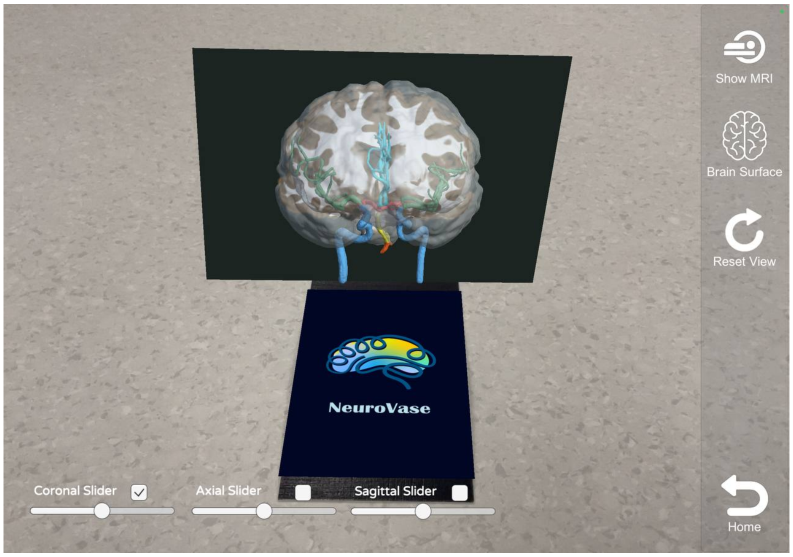


Figure 3.8: The vascular phase showing the MRI Coronal visualization.

with 18 multiple-choice questions to gauge their level of knowledge on neuroanatomy and related physiology. Following this, the participant followed our AR-based learning modules, which were accompanied by a series of cue cards in a predetermined order of lobar anatomy, arterial anatomy, and vascular territories. During the AR-based learning, the users were instructed to only use the front of the cue cards and not to read the educational content on the back to properly assess the learning materials designed for the iPad. Upon completing the learning modules, they were instructed to finish a post-study quiz, which was identical to the pre-study to evaluate the learning outcome. Once this was done, the participants were invited to play with the cue cards to examine the educational content on their backs.

Towards the end of the study, each participant was presented with a semi-quantitative questionnaire to assess their experience with our software system. The questionnaire consisted of three parts. While the first part is the System Usability Scale (SUS) questionnaire [32], which is widely used to validate the usability of software systems. In the second part, we included five customized user experience (UX) questions on the 1-to-5 Likert scale (1=strongly disagree, 5=strongly agree) to assess the perceived level of user engagement, joy, software's usefulness for learning, cue card design quality, and effectiveness of AR visualization for learning. These questions offer additional insights into the user experience. In the last part of the questionnaire, the participants were encouraged to provide comments regarding their perceived positives and negatives of the system, as well as suggestions to improve the system.

To help better understand the participants' profiles, we also asked the participants to rate their familiarity with AR technology and neuroanatomy, on a scale of 1-5, with 1 being familiar and 5 being unfamiliar.

3.4 Data analysis

For the pre- and post-study quizzes, we scored them out of 100%, and compared the $\%$ scores using a two-sided paired-sample t-test to confirm the learning gain among the participants. The SUS evaluation consists of 10 questions rated on a scale of 1-5 (strongly disagree to strongly agree), evaluating system complexity, ease of use, and confidence when using a software system. For each of the scores of the 10 questions x, odd-numbered questions are scored as $x-1$ while even-numbered questions are scored as $5-x$. The total score is then summed and multiplied by 2.5 to yield the final score, with a maximum of 100, and a score above 68 indicating good usability [32]. To evaluate the collected SUS scores, we performed a one-sample t-test to determine if the results were significantly higher than 68. For each SUS sub-score and the customized UX questions, we compared the results to a neutral response (score=3), also using one-sample t-tests. A p-value < 0.05 was considered to indicate statistical significance for all tests.

For the qualitative data from participants' free form questions, we reviewed all content and summarized the key insights based on their frequency among participants. These insights provide a better understanding of the semi-quantitative assessments and suggest potential directions for future improvements.

Among these participants, based on a Likert scale from 1 to 5, the average familiarity with AR was 2 out of 5, indicating some level of familiarity with the technology, while the average familiarity with brain anatomy was 3.9 out of 5, indicating somewhat unfamiliarity, prior to participating in the study.

3.5 Results

3.5.1 Educational outcome assessment

Based on our evaluation, as shown in Table 3.1, the 20 participants' performance showed a significant improvement, with the pre-study quiz scores averaging 40.83% and the post-study quiz scores averaging 70.28%. With the t-test, the post-study quiz had a significantly higher score than the pre-study one, thus confirming the effectiveness of our educational AR system.

Quiz Scores	
Pre-Quiz Scores	40.83% ± 7.71%
Post-Quiz Scores	70.28% ± 14.11%

Table 3.1: Comparison of pre-study and post-study quiz scores

3.5.2 System Usability Scale

The overall SUS score calculated based on participant responses for this system is 90.0±5.7, which is significantly higher than the score of 68 ($p<0.001$), indicating excellent usability of the NeuroVase system. To further inspect the participants' responses to individual SUS sub-questions, we listed their scores in Table 3.2 and the distributions of the scores across the participants for the positive and negative questions are shown in Fig. 3.9. For all sub-questions, we found their responses to be significantly better than a "neutral" attitude ($p<0.05$).

Table 3.2: System Usability Scale Sub-question Scores

System Usability Scale Sub-questions	**Score**
I think that I would like to use this system frequently.	4.35 ± 0.67
I found this system unnecessarily complex.	1.30 ± 0.57
I thought this system was easy to use.	4.60 ± 0.60
I think that I would need assistance to be able to use this system.	1.20 ± 0.52
I found the various functions in this system were well integrated.	4.20 ± 0.62
I thought there was too much inconsistency in this system.	1.45 ± 0.76
I would imagine that most people would learn to use this system very quickly.	4.80 ± 0.52
I found this system very cumbersome/awkward to use.	1.50 ± 0.83
I felt very confident using this system.	4.65 ± 0.49
I needed to learn a lot of things before I could get going with this system.	1.15 ± 0.37

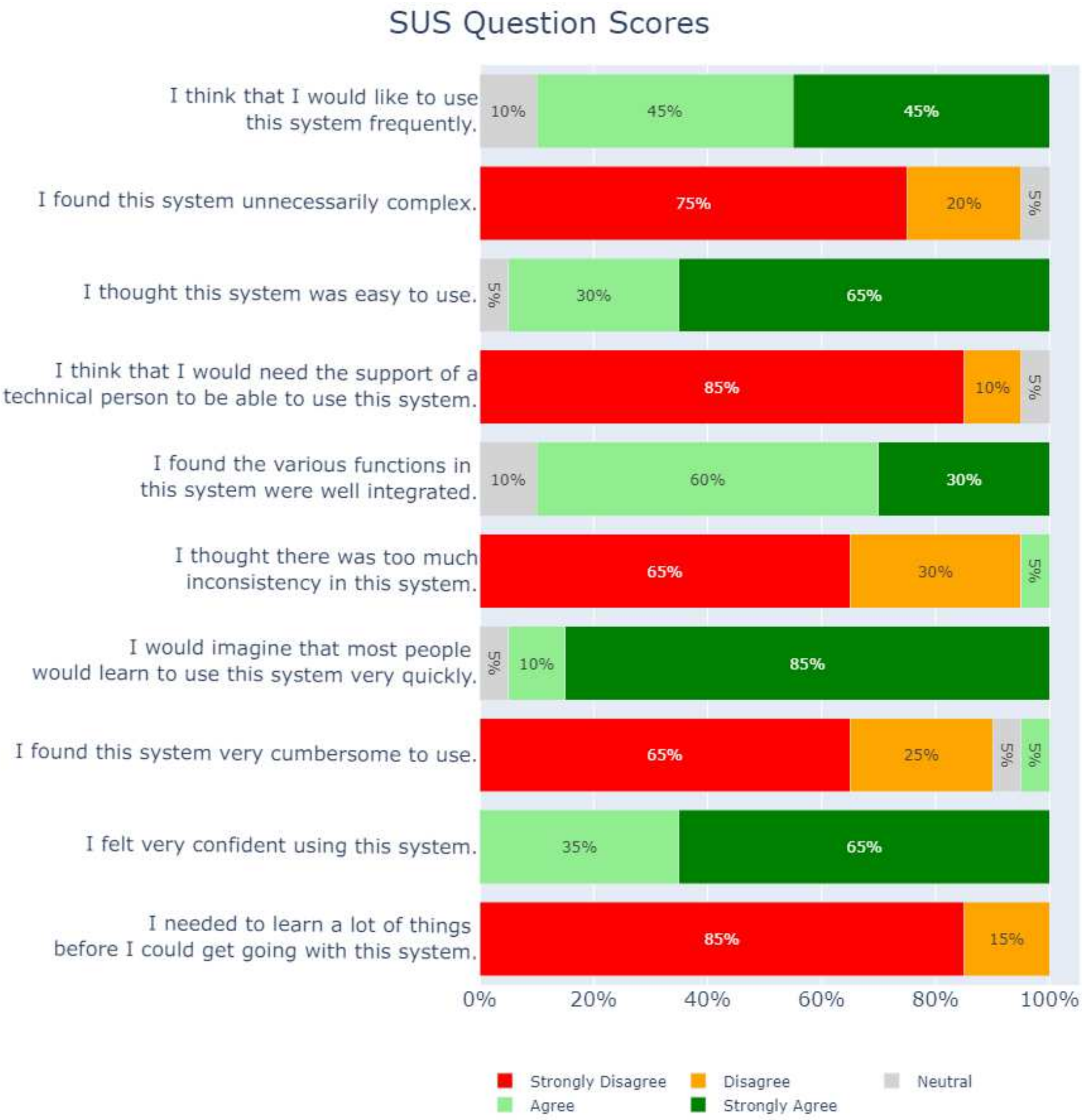


Figure 3.9: Distribution of SUS Sub-Question Scores Across Participants

3.5.3 User Experience Assessment

In addition to SUS, five customized questions were posed to probe additional dimensions of the UX concerning the factors potentially related to learning outcomes and the effectiveness of system design elements. These questions and the box plots of their corresponding scores are shown in Fig. 3.10, with a higher score being more desirable. With statistical analysis, we confirmed that all questions received responses that are significantly better than a neutral score of 3. From all 20 participants, 87% felt engaged when using the mobile application. 89% thought that the mobile application was pleasant to use. 91% of users found the mobile application useful for learning, and an equal percentage of 91% found that the cue cards are well designed. Additionally, 86% of users felt that the AR helps them learn the content. These results indicate that the mobile application was well-received and effective in engaging users and aiding their learning process.

3.5.4 Free-form feedback

We obtained free-form feedback from 19 out of 20 participants to better understand the participants' ratings for the semi-quantitative questionnaires and solicit future improvement for the proposed system. We summarize the feedback in Table 3.3. For the positive feedback, participants mentioned 3D visualization was helpful, providing better perspectives and view options (11/19), and praised the ease of use (11/19). These echo the high scores for the SUS (90.0±5.7) and the customized UX question regarding the usefulness of AR visualization in aiding the learning experience (4.30±0.86). In addition, many participants (7/19) found the user interaction strategy smooth and well designed. On the other hand, some participants also noticed that the virtual content triggering mechanism with the cue cards can suffer from glitches at times (6/19) and a small number of participants (4/19) felt that the educational content is overly detailed. Lastly, in terms of suggestions for improving the system, half of the participants wished for richer 3D anatomical models and additional explanations for certain medical jargon for lay users while some suggested further improvement of content interaction, such as finger-gesture-based model rotation and free text box repositioning. Interestingly, a couple of participants suggested adding blood flow animation, which could enhance the understanding of the vascular anatomy.

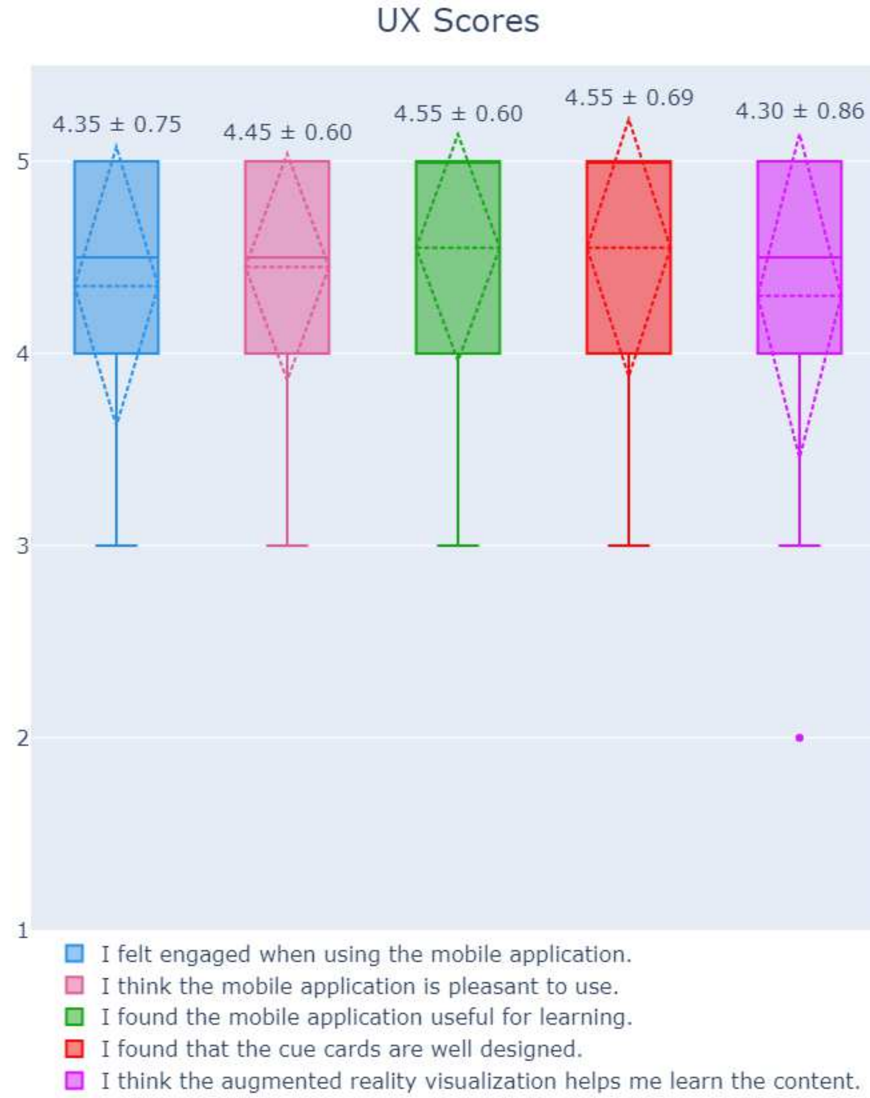


Figure 3.10: Boxplots of UX Question Scores Across Participants.

Table 3.3: Summary of Participants' Freeform Feedback on NeuroVase

Feedback Category	**Type**	**Description**	**Count**
Ease of Use	Positive	Easy to use, intuitive, and user-friendly with clear instructions.	11/19
Interaction Quality	Positive	Smooth and interactive interactions, fast processing.	7/19
Design and UI	Positive	Well-designed, attractive UI, and well-integrated system.	3/19
3D Visualization	Positive	Highly praised for helpful and detailed visualization options.	12/19
Learning Enhancement	Positive	Boosts learning and engaging.	2/19
Additional Attributes	Positive	Interesting content, immersive experience, and clear information.	5/19
Cue Card Issues	Negative	Problems with cue cards loading and management.	7/19
Content Overload	Negative	Reports of too much information and overly detailed descriptions.	4/19
Interaction Issues	Negative	Issues with rotation, text placement, and tracking.	6/19
Content Suggestions	Suggestion	More detailed content on the 3D models and additional explanations on medical terms.	10/19
Interaction Improvements	Suggestion	Improve rotation, text box repositioning, and view resetting.	8/19
Feature Enhancements	Suggestion	Add new features like blood flow visualization	2/19

3.6 Discussion

Despite the advancements in AR/VR-based neuroanatomy education, several domains are still under-explored. One significant knowledge gap remains in the focus on VR/AR-based vascular anatomy and stroke education, which is crucial for understanding and treating neurological conditions. Existing mixed reality applications predominantly address general brain anatomy and connectivity, with relatively simple learning content. NeuroVase, on the other hand, fills the gap by offering engaging learning materials tailored for stroke care, developed in collaboration with a clinical specialist. Our NeuroVase system distinguishes itself from the AR system proposed by Moro et al. [25] in several key aspects. First, unlike their AR system, which utilizes a cube as a physical medium for AR interactions, we employ more practical cue cards that allow more flexible virtual learning content management. Second, the work of Moro et al. [25] primarily focuses on patient education, and thus only general brain divisions are provided for virtual brain model visualization. In comparison, the target audience of our system focuses on medical students and professionals, requiring us to include richer anatomical learning materials for textural description and imaging data (as virtual model and MRI visualization). This comprehensive content, makes NeuroVase a potentially more versatile and helpful tool in medical education than that featured in the the study of Moro et al. [25]. Our NeuroVase system features a structured educational curriculum that progresses through three distinct phases: lobar anatomy, vascular anatomy, and arterial territorial anatomy, and we recommend the user to follow these three learning modules in sequence as the knowledge of the later module builds upon the previous one. This curriculum design reinforces knowledge acquisition and greatly enhances spatial understanding of complex neuroanatomy. In addition, this also allows additional learning modules to be augmented based on existing ones to further enrich the learning experience.

The interface and interaction design choices for NeuroVase were driven by the need to create an intuitive, engaging, and flexible neurovascular anatomy learning tool. The application's tablet-based platform leverages the widespread accessibility and familiarity of tablet devices, enhancing user-friendliness and broad accessibility. Physical cue cards serve as both a digital enhancement when used with the app and as standalone study aids, creating a dual functionality that supports diverse learning scenarios and reinforces knowledge retention. While the main card sets the position for the virtual anatomical model, the trigger cards placed beside the main card update the AR view to display content represented by the trigger card. This ability to manipulate and inspect the digital model from different angles enhances spatial learning of the target anatomical structures. Additionally, translation and rotation can be achieved by repositioning just the master card. To prevent accidental content switching, finger-tapping to select anatomy is disabled. Cue cards are used in a designated order (lobar anatomy, arterial system, and vascular territories) to guide the learning curriculum effectively. Unlike simply reading the content, through augmented reality, the user can manipulate the 3D model in a self-directed way and take control of their own learning.

The user study revealed several key observations and trends. Participants showed a significant 63.52% improvement in their knowledge of neuroanatomy, as indicated by the pre-quiz and post-quiz results, demonstrating the effectiveness of NeuroVase as an educational tool. The SUS results further confirm the application's usability, with a high mean score of 90 out of 100, suggesting that the users found NeuroVase easy to use, intuitive, and user-friendly. Furthermore, the customized UX questionnaire also indicates high levels of engagement, perceived usefulness, and enjoyment for using the system, which are crucial factors for enhanced learning outcomes. In addition, the quality of cue card design and effectiveness of AR visualization, which are primary features of our system were also highly rated by the participants. Finally, free-form feedback highlighted the helpfulness of 3D visualization and ease of use. While most feedback was positive, some issues, such as cue card loading glitches reported by participants, need attention. As noted by Mu et al. [27], AR's camera tracking can be affected by lighting conditions. Similarly, our study found that such environmental factors could also disrupt cue card feature recognition with Vuforia, underscoring the importance of controlled lighting to optimize the mobile AR experience.

Based on feedback from the user study, several areas for improvement have been identified to enhance system performance and interactions. These future enhancements include improving finger gesture interaction (e.g., model rotation) and resolving the cue card loading glitch problems. To enhance the rotation feature in the NeuroVase system based on user feedback, we plan to implement a two-finger gesture control, instead of one-finger, for more natural and stable model manipulation. Additionally, we would also test a "rotation slider" within the user interface, allowing for precise adjustments with minimal effort. Moreover, to address the cue card loading glitches in the NeuroVase system, which also tend to plague similar AR software applications, we plan to refine the card design by incorporating more distinct graphic patterns on each card, which will aid the Vuforia engine in better differentiating them. Additionally, we will implement guidelines for optimal room lighting conditions to minimize reflections on the cards, ensuring a more consistent and reliable AR recognition experience. These changes aim to improve user interaction by providing more control options and accommodating different user preferences for navigating 3D models. In the near future, the first version of NeuroVase will also be developed for virtual reality to compare user interactions and learning effectiveness in different data visualization modes. Finally, future research will incorporate a more diverse demographic, particularly with older adults and individuals with varying levels of technological proficiency, to better understand the generalizability of NeuroVase's effectiveness. These improvements and studies aim to achieve the best possible outcomes for NeuroVase in medical education.

3.7 Conclusion

In this work, we introduced NeuroVase, a novel mobile AR application for the education of cerebrovascular system and territories in the context of stroke care. By leveraging physical cue cards as the medium to interact with AR learning content while serving as a convenient extension for knowledge point review, the proposed system was proven to be a user-friendly, engaging, and effective educational tool through user studies. NeuroVase offers a valuable supplementary resource, providing interactive 3D visualizations and engaging and enjoyable learning experiences that traditional methods alone often cannot achieve.

Chapter 4

Conclusion

In this thesis, we developed NeuroVase, a mobile augmented reality (AR) application designed to enhance neuroanatomy education, particularly focusing on stroke education. NeuroVase offers users an immersive and interactive platform to explore complex anatomical structures through detailed 3D visualization. Our application integrates innovative features, such as physical cue cards that interact with virtual anatomies and provide textual learning materials, offering a comprehensive educational tool that addresses the limitations of traditional 2D illustrations and physical dissections. Additionally, NeuroVase's tablet-based design offers convenience, accessibility, and practicality, catering to a wide range of users without the need for expensive or specialized equipment. Our system has shown impressive results in user studies, not only in usability but also in enhancing educational effectiveness. The significant improvements in quiz scores and positive feedback from the user study highlight NeuroVase's potential as both an academic and clinical education tool. Furthermore, NeuroVase's modular design of learning materials allows for flexibility and customization, enabling the addition of new educational content in the future.

In conclusion, NeuroVase presents a significant contribution in the use of augmented reality for neuroanatomy education, specifically for the cerebrovascular system. It provides an immersive, engaging, and highly effective learning experience that bridges the gap between traditional methods and modern interactive tools. We will continue to build additional interactive analysis functions for the system in the future.

4.1 Future Work

First and foremost, as mentioned in Section 3.5.3, based on the feedback from the user study, there is still room for further improvements in the system performance and interactions. First, we plan to improve the gesture-based rotation feature and overcome the cue card loading glitch problem with software optimization. Second, in response to the users' popular demand, we will incorporate more detailed vascular models to allow the inspection of additional anatomical details. As mentioned in the users' suggestions, demonstrating the blood flow is an interesting option that could enhance the engagement of the users for the learning content. Last but not least, as a comparison, it can be beneficial to adapt NeuroVase in virtual reality on wearable devices, such as Meta Quest 3 to further confirm the benefits and drawbacks between AR and VR for cerebrovascular anatomy education. As the current investigation of medical education still primarily relies on relatively simple knowledge points (e.g., learning of brain lobes), future research with more elaborate educational content, such as the case of NeuroVase would be beneficial to further tailor effective data visualization and interaction strategies to ensure the learning quality and efficiency.

Appendix A

Designs

A.1 Cue Card Design

The full design of the cue cards for three different learning modules are demonstrated in Figs. A.1 A.2 A.3 A.4 A.5 A.6 below.

A.2 Quiz

The pre-quiz questions are demonstrated in Figs. A.7 A.8 A.9.

A.3 Ethics Approval Form

The ethics approval form is demonstrated in Fig. A.10.

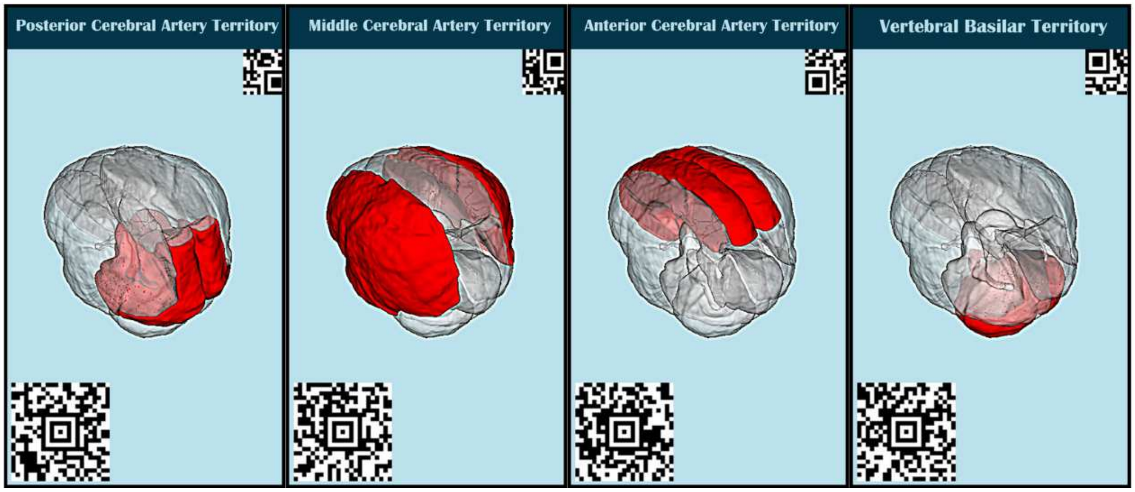
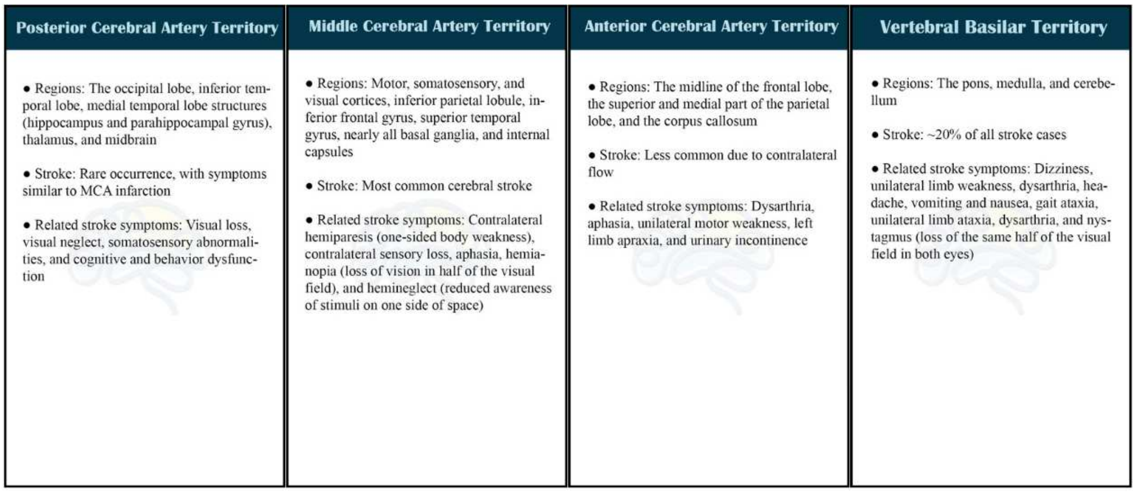


Figure A.1: Vascular Territory Module Cue Cards: Front View



Posterior Cerebral Artery Territory

- Regions: The occipital lobe, inferior temporal lobe, medial temporal lobe structures (hippocampus and parahippocampal gyrus), thalamus, and midbrain

- Stroke: Rare occurrence, with symptoms similar to MCA infarction

- Related stroke symptoms: Visual loss, visual neglect, somatosensory abnormalities, and cognitive and behavior dysfunction

Middle Cerebral Artery Territory

- Regions: Motor, somatosensory, and visual cortices, inferior parietal lobule, inferior frontal gyrus, superior temporal gyrus, nearly all basal ganglia, and internal capsules

- Stroke: Most common cerebral stroke

- Related stroke symptoms: Contralateral hemiparesis (one-sided body weakness), contralateral sensory loss, aphasia, hemianopia (loss of vision in half of the visual field), and hemineglect (reduced awareness of stimuli on one side of space)

Anterior Cerebral Artery Territory

- Regions: The midline of the frontal lobe, the superior and medial part of the parietal lobe, and the corpus callosum

- Stroke: Less common due to contralateral flow

- Related stroke symptoms: Dysarthria, aphasia, unilateral motor weakness, left limb apraxia, and urinary incontinence

Vertebral Basilar Territory

- Regions: The pons, medulla, and cerebellum

- Stroke: ~20% of all stroke cases

- Related stroke symptoms: Dizziness, unilateral limb weakness, dysarthria, headache, vomiting and nausea, gait ataxia, unilateral limb ataxia, dysarthria, and nystagmus (loss of the same half of the visual field in both eyes)

Figure A.2: Vascular Territory Module Cue Cards: Back View

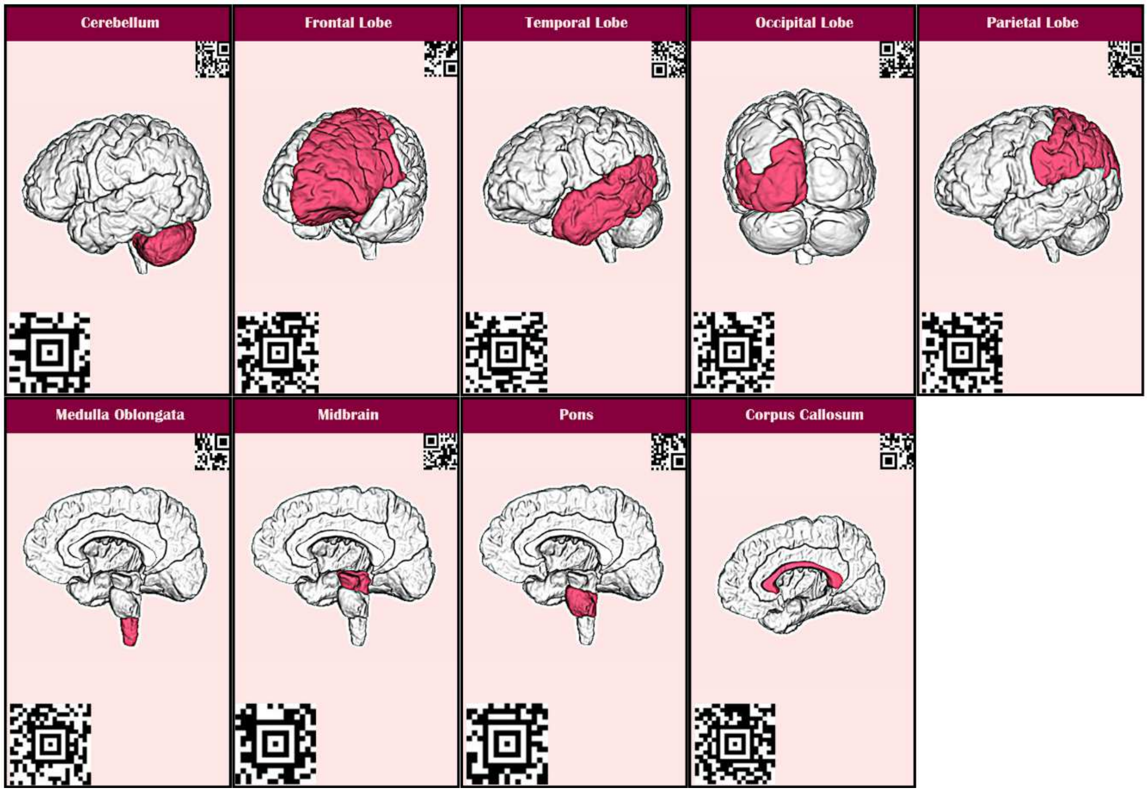
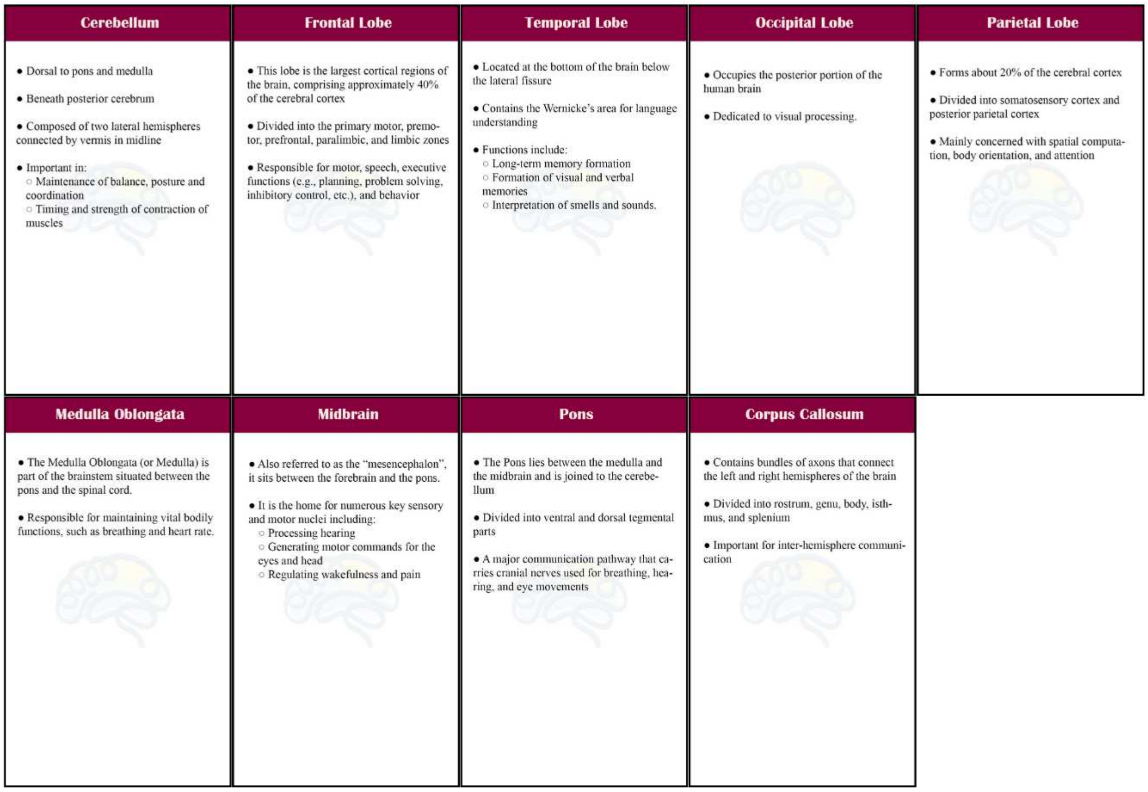


Figure A.3: Lobar Phase Cards



Cerebellum

- Dorsal to pons and medulla
- Beneath posterior cerebrum
- Composed of two lateral hemispheres connected by vermis in midline
- Important in:
  - Maintenance of balance, posture and coordination
  - Timing and strength of contraction of muscles

Frontal Lobe

- This lobe is the largest cortical regions of the brain, comprising approximately 40% of the cerebral cortex
- Divided into the primary motor, premotor, prefrontal, paralimbic, and limbic zones
- Responsible for motor, speech, executive functions (e.g., planning, problem solving, inhibitory control, etc.), and behavior

Temporal Lobe

- Located at the bottom of the brain below the lateral fissure
- Contains the Wernicke's area for language understanding
- Functions include:
  - Long-term memory formation
  - Formation of visual and verbal memories
  - Interpretation of smells and sounds.

Occipital Lobe

- Occupies the posterior portion of the human brain
- Dedicated to visual processing.

Parietal Lobe

- Forms about 20% of the cerebral cortex
- Divided into somatosensory cortex and posterior parietal cortex
- Mainly concerned with spatial computation, body orientation, and attention

Medulla Oblongata

- The Medulla Oblongata (or Medulla) is part of the brainstem situated between the pons and the spinal cord.
- Responsible for maintaining vital bodily functions, such as breathing and heart rate.

Midbrain

- Also referred to as the "mesencephalon", it sits between the forebrain and the pons.
- It is the home for numerous key sensory and motor nuclei including:
  - Processing hearing
  - Generating motor commands for the eyes and head
  - Regulating wakefulness and pain

Pons

- The Pons lies between the medulla and the midbrain and is joined to the cerebellum
- Divided into ventral and dorsal tegmental parts
- A major communication pathway that carries cranial nerves used for breathing, hearing, and eye movements

Corpus Callosum

- Contains bundles of axons that connect the left and right hemispheres of the brain
- Divided into rostrum, genu, body, isthmus, and splenium
- Important for inter-hemisphere communication

Figure A.4: Lobar Anatomy Module Cue Cards: Back View

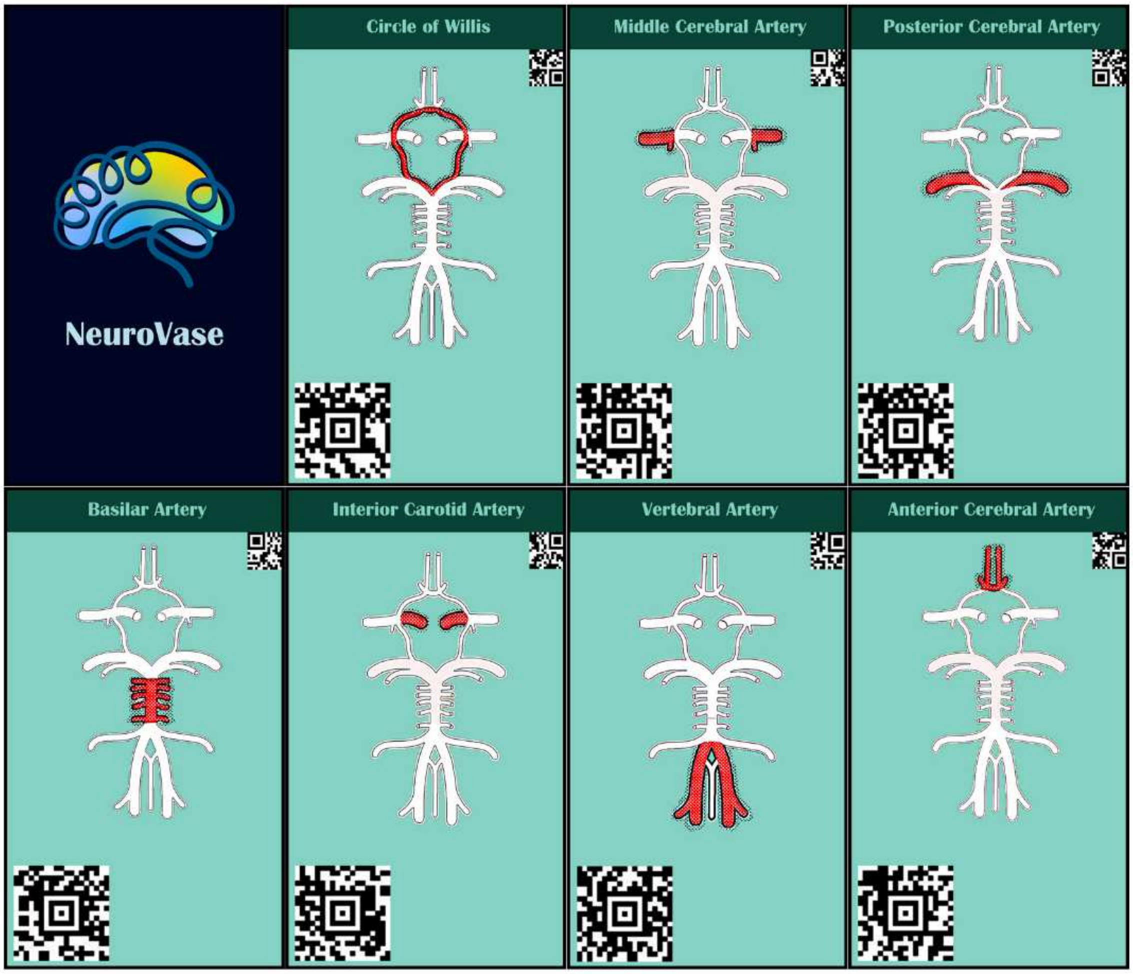
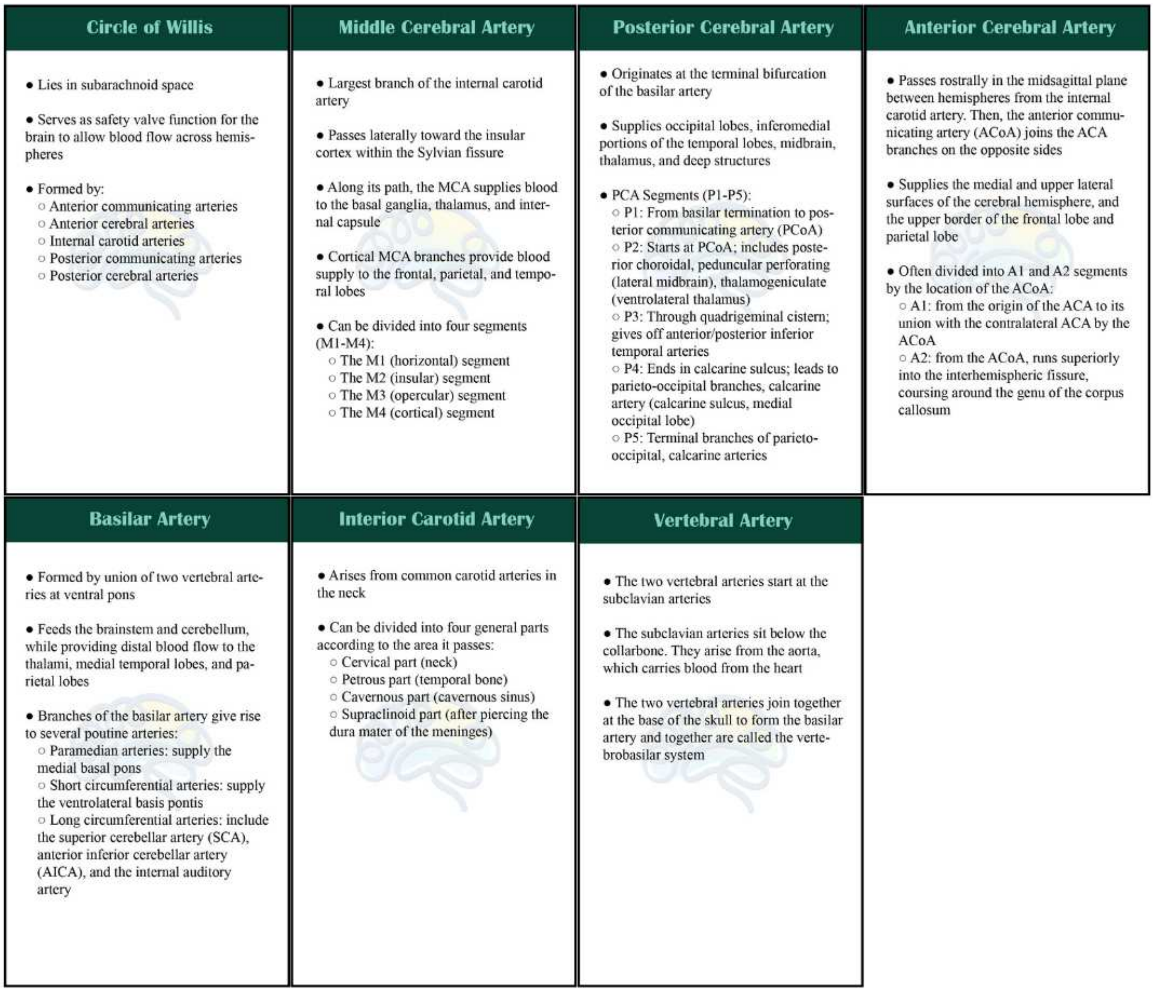


Figure A.5: Main Card and Vascular Module Cue Cards: Front View



Circle of Willis

- Lies in subarachnoid space
- Serves as safety valve function for the brain to allow blood flow across hemispheres
- Formed by:
  - ○ Anterior communicating arteries
  - ○ Anterior cerebral arteries
  - ○ Internal carotid arteries
  - ○ Posterior communicating arteries
  - ○ Posterior cerebral arteries

Middle Cerebral Artery

- Largest branch of the internal carotid artery
- Passes laterally toward the insular cortex within the Sylvian fissure
- Along its path, the MCA supplies blood to the basal ganglia, thalamus, and internal capsule
- Cortical MCA branches provide blood supply to the frontal, parietal, and temporal lobes
- Can be divided into four segments (M1-M4):
  - ○ The M1 (horizontal) segment
  - ○ The M2 (insular) segment
  - ○ The M3 (opercular) segment
  - ○ The M4 (cortical) segment

Posterior Cerebral Artery

- Originates at the terminal bifurcation of the basilar artery
- Supplies occipital lobes, inferomedial portions of the temporal lobes, midbrain, thalamus, and deep structures
- PCA Segments (P1-P5):
  - ○ P1: From basilar termination to posterior communicating artery (PCoA)
  - ○ P2: Starts at PCoA; includes posterior choroidal, peduncular perforating (lateral midbrain), thalamogeniculate (ventrolateral thalamus)
  - ○ P3: Through quadrigeminal cistern; gives off anterior/posterior inferior temporal arteries
  - ○ P4: Ends in calcarine sulcus; leads to parieto-occipital branches, calcarine artery (calcarine sulcus, medial occipital lobe)
  - ○ P5: Terminal branches of parieto-occipital, calcarine arteries

Anterior Cerebral Artery

- Passes rostrally in the midsagittal plane between hemispheres from the internal carotid artery. Then, the anterior communicating artery (ACoA) joins the ACA branches on the opposite sides
- Supplies the medial and upper lateral surfaces of the cerebral hemisphere, and the upper border of the frontal lobe and parietal lobe
- Often divided into A1 and A2 segments by the location of the ACoA:
  - ○ A1: from the origin of the ACA to its union with the contralateral ACA by the ACoA
  - ○ A2: from the ACoA, runs superiorly into the interhemispheric fissure, coursing around the genu of the corpus callosum

Basilar Artery

- Formed by union of two vertebral arteries at ventral pons
- Feeds the brainstem and cerebellum, while providing distal blood flow to the thalami, medial temporal lobes, and parietal lobes
- Branches of the basilar artery give rise to several poutine arteries:
  - ○ Paramedian arteries: supply the medial basal pons
  - ○ Short circumferential arteries: supply the ventrolateral basis pontis
  - ○ Long circumferential arteries: include the superior cerebellar artery (SCA), anterior inferior cerebellar artery (AICA), and the internal auditory artery

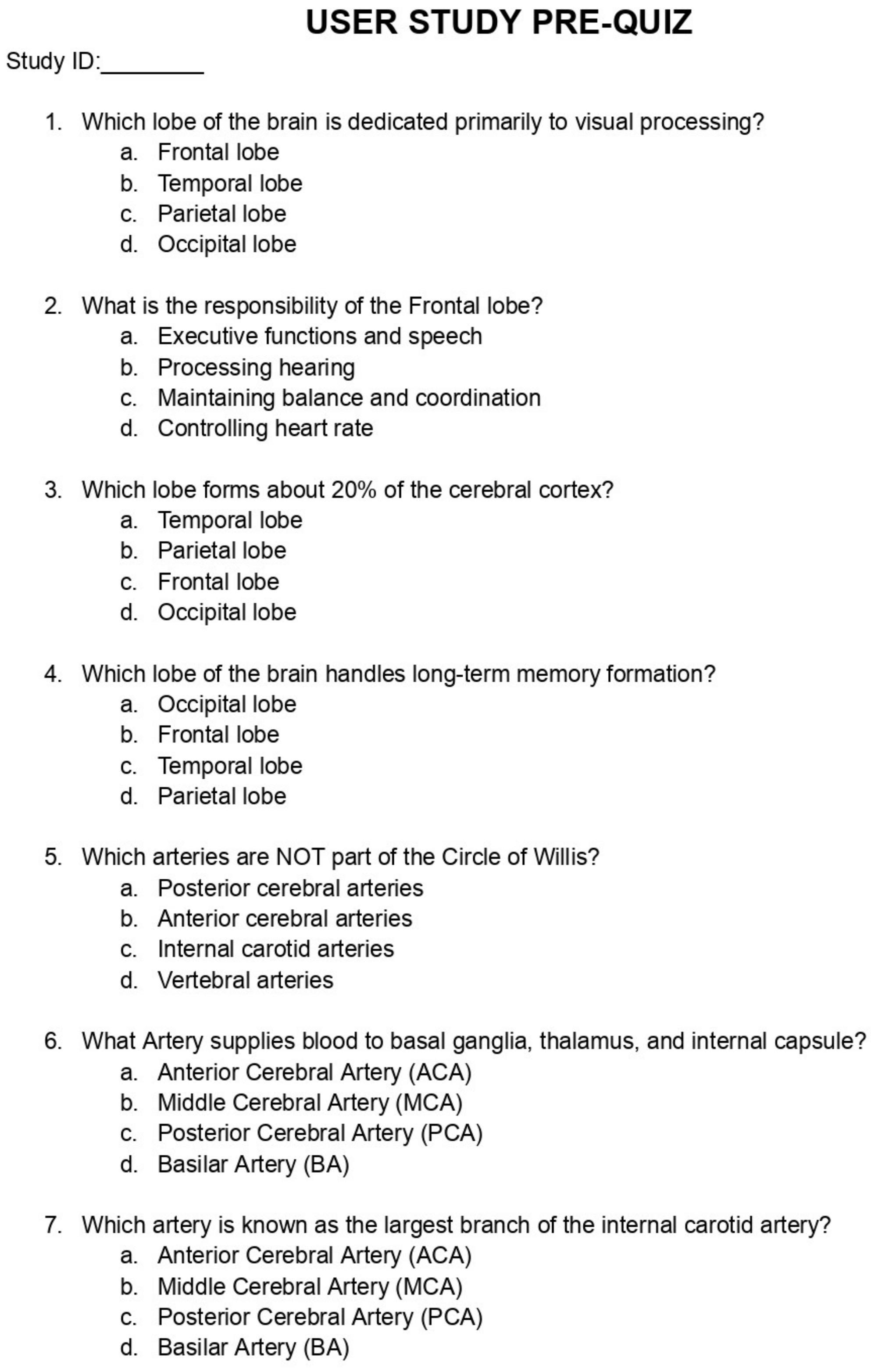
Interior Carotid Artery

- Arises from common carotid arteries in the neck
- Can be divided into four general parts according to the area it passes:
  - ○ Cervical part (neck)
  - ○ Petrous part (temporal bone)
  - ○ Cavernous part (cavernous sinus)
  - ○ Supraclinoid part (after piercing the dura mater of the meninges)

Vertebral Artery

- The two vertebral arteries start at the subclavian arteries
- The subclavian arteries sit below the collarbone. They arise from the aorta, which carries blood from the heart
- The two vertebral arteries join together at the base of the skull to form the basilar artery and together are called the vertebrobasilar system

Figure A.6: Vascular Module Cue Cards: Back View



USER STUDY PRE-QUIZ

Study ID:________

1. Which lobe of the brain is dedicated primarily to visual processing?
    a. Frontal lobe
    b. Temporal lobe
    c. Parietal lobe
    d. Occipital lobe

2. What is the responsibility of the Frontal lobe?
    a. Executive functions and speech
    b. Processing hearing
    c. Maintaining balance and coordination
    d. Controlling heart rate

3. Which lobe forms about 20% of the cerebral cortex?
    a. Temporal lobe
    b. Parietal lobe
    c. Frontal lobe
    d. Occipital lobe

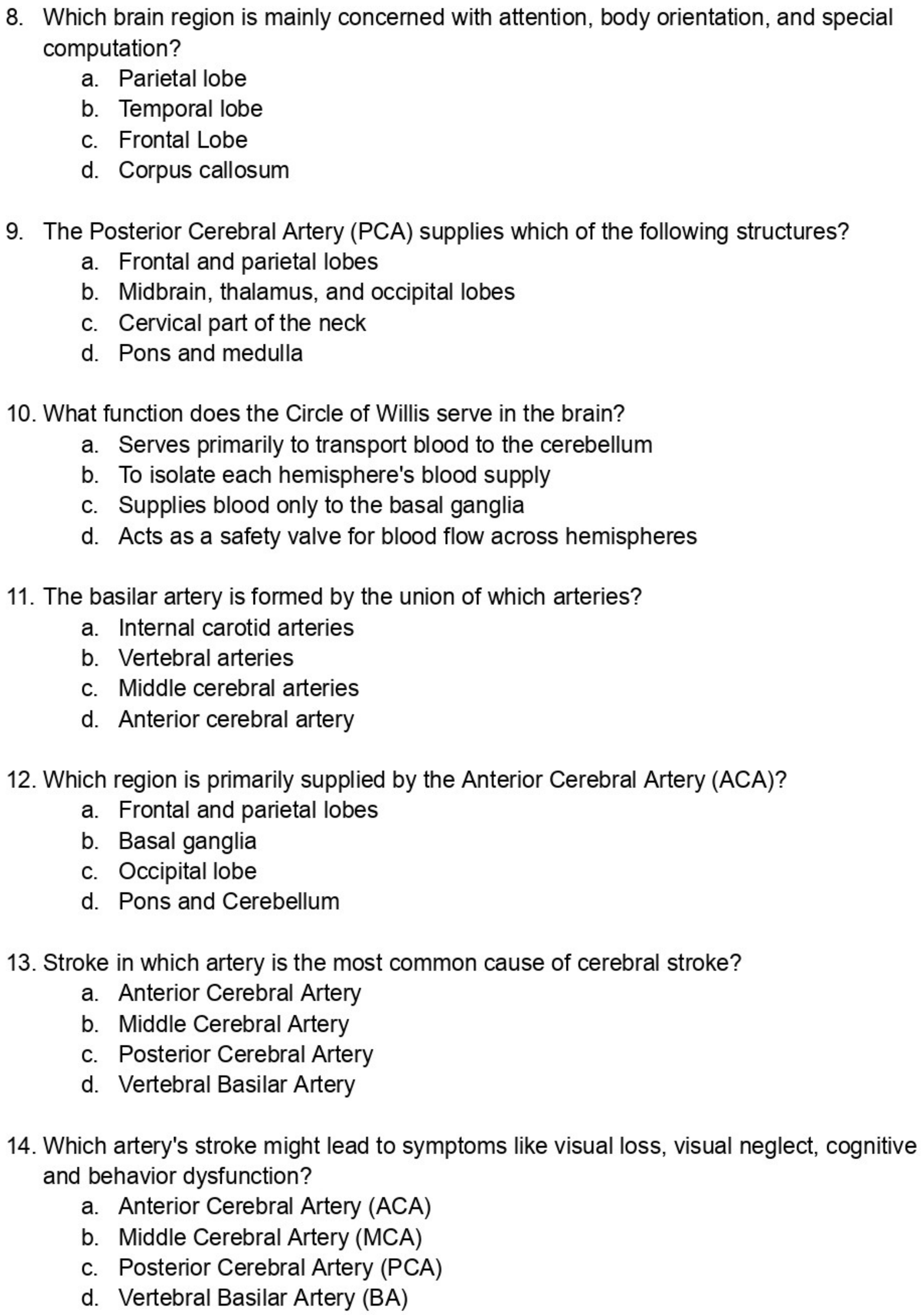
4. Which lobe of the brain handles long-term memory formation?
    a. Occipital lobe
    b. Frontal lobe
    c. Temporal lobe
    d. Parietal lobe

5. Which arteries are NOT part of the Circle of Willis?
    a. Posterior cerebral arteries
    b. Anterior cerebral arteries
    c. Internal carotid arteries
    d. Vertebral arteries

6. What Artery supplies blood to basal ganglia, thalamus, and internal capsule?
    a. Anterior Cerebral Artery (ACA)
    b. Middle Cerebral Artery (MCA)
    c. Posterior Cerebral Artery (PCA)
    d. Basilar Artery (BA)

7. Which artery is known as the largest branch of the internal carotid artery?
    a. Anterior Cerebral Artery (ACA)
    b. Middle Cerebral Artery (MCA)
    c. Posterior Cerebral Artery (PCA)
    d. Basilar Artery (BA)

Figure A.7: Pre Quiz First Page



8. Which brain region is mainly concerned with attention, body orientation, and special computation?
    a. Parietal lobe
    b. Temporal lobe
    c. Frontal Lobe
    d. Corpus callosum

9. The Posterior Cerebral Artery (PCA) supplies which of the following structures?
    a. Frontal and parietal lobes
    b. Midbrain, thalamus, and occipital lobes
    c. Cervical part of the neck
    d. Pons and medulla

10. What function does the Circle of Willis serve in the brain?
    a. Serves primarily to transport blood to the cerebellum
    b. To isolate each hemisphere's blood supply
    c. Supplies blood only to the basal ganglia
    d. Acts as a safety valve for blood flow across hemispheres

11. The basilar artery is formed by the union of which arteries?
    a. Internal carotid arteries
    b. Vertebral arteries
    c. Middle cerebral arteries
    d. Anterior cerebral artery

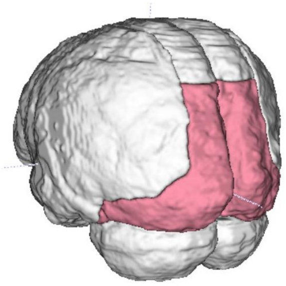
12. Which region is primarily supplied by the Anterior Cerebral Artery (ACA)?
    a. Frontal and parietal lobes
    b. Basal ganglia
    c. Occipital lobe
    d. Pons and Cerebellum

13. Stroke in which artery is the most common cause of cerebral stroke?
    a. Anterior Cerebral Artery
    b. Middle Cerebral Artery
    c. Posterior Cerebral Artery
    d. Vertebral Basilar Artery

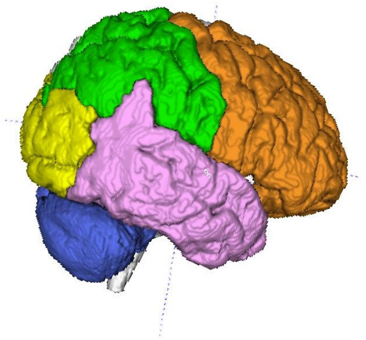
14. Which artery's stroke might lead to symptoms like visual loss, visual neglect, cognitive and behavior dysfunction?
    a. Anterior Cerebral Artery (ACA)
    b. Middle Cerebral Artery (MCA)
    c. Posterior Cerebral Artery (PCA)
    d. Vertebral Basilar Artery (BA)

Figure A.8: Pre Quiz Second Page

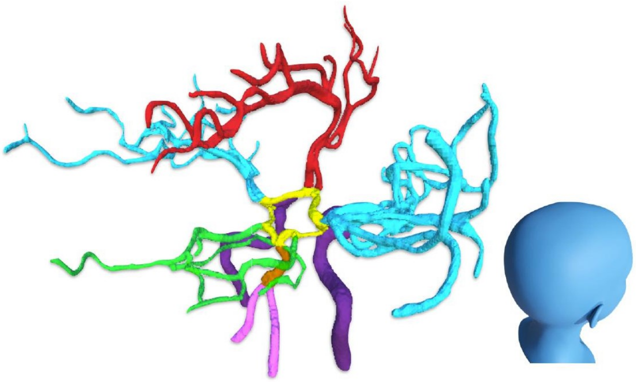
15. What artery supplies this territory?
    a. Anterior Cerebral Artery
    b. Vertebral Basilar Artery
    c. Posterior Cerebral Artery
    d. Middle Cerebral Artery



16. What is the name of the GREEN region?
    a. Parietal Lobe
    b. Frontal Lobe
    c. Occipital Lobe
    d. Temporal Lobe



17. What is the name of the RED Artery?
    a. Anterior Cerebral Artery
    b. Vertebral Artery
    c. Posterior Cerebral Artery
    d. Middle Cerebral Artery



18. Referring to the image, which artery is represented by the GREEN color?
    a. Posterior Cerebral Artery
    b. Middle Cerebral Artery
    c. Anterior Cerebral Artery
    d. Interior Carotid Artery

Figure A.9: Pre Quiz Last Page

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CERTIFICATION OF ETHICAL ACCEPTABILITY
FOR RESEARCH INVOLVING HUMAN SUBJECTS

Name of Applicant:	Dr. Yiming Xiao
Department:	Gina Cody School of Engineering and Computer Science\Computer Science and Software Engineering
Agency:	Fonds Québecois de la Recherche sur la Nature et les Technologies Concordia University
Title of Project:	Mobile augmented reality applications for medical education and visualization
Certification Number:	30019398

Valid From: December 12, 2023 To: December 11, 2024

The members of the University Human Research Ethics Committee have examined the application for a grant to support the above-named project, and consider the experimental procedures, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects.

Richard DeMont

Dr. Richard DeMont, Chair, University Human Research Ethics Committee

Figure A.10: Ethics approval form

Bibliography

[1] M. Arantes, Joana Arantes, and Maria Ferreira. Tools and resources for neuroanatomy education: A systematic review. *BMC Medical Education*, 18, 05 2018.

[2] Fabio Arena, Mario Collotta, Giovanni Pau, and Francesco Termine. An overview of augmented reality. *Computers*, 11(2), 2022.

[3] John Brooke. System usability scale (sus): a quick-and-dirty method of system evaluation user information. *Reading, UK: Digital equipment co ltd*, 43:1–7, 1986.

[4] L. Caplan. *Caplan's Stroke: A Clinical Approach*. Caplan's Stroke a Clinical Approach. Elsevier Health Sciences, 2009.

[5] Moisés Carrasco and Po-Han Chen. Application of mixed reality for improving architectural design comprehension effectiveness. *Automation in Construction*, 126:103677, 06 2021.

[6] R.L. Drake, W. Vogl, and A.W.M. Mitchell. *Gray's Anatomy for Students*. Gray's Anatomy Series. Elsevier, 2019.

[7] Alexei J Drummond and Andrew Rambaut. Beast: Bayesian evolutionary analysis by sampling trees. *BMC evolutionary biology*, 7:1–8, 2007.

[8] Nell K. Duke. What matters most when you're evaluating edtech tools, 2020. Edutopia article discussing key considerations for evaluating educational technology tools, including efficacy, student experience, intrinsic motivation, and the teacher experience.

[9] Alejandro F Frangi, Wiro J Niessen, Koen L Vincken, and Max A Viergever. Multiscale

vessel enhancement filtering. In *Medical Image Computing and Computer-Assisted Intervention—MICCAI'98: First International Conference Cambridge, MA, USA, October 11–13, 1998 Proceedings 1*, pages 130–137. Springer, 1998.

[10] James Giles. Clinical neuroscience attachments: a student's view of 'neurophobia'. *The clinical teacher*, 7(1):9–13, 2010.

[11] Lorna Gloy, Thomas Cheng, Jenny Wong, and Matthew Lam. Efficiency and retention in vr-based neuroanatomy learning: A comparative study. *Educational Technology Research and Development*, 70(4):1019–1035, 2022.

[12] Zhaoyuan Gong, Jing Guo, Bin Liu, Yang Guo, Cuicui Cheng, Yin Jiang, Ning Liang, Mingzhi Hu, Tian Song, Lu Yang, et al. Mechanisms of immune response and cell death in ischemic stroke and their regulation by natural compounds. *Frontiers in Immunology*, 14:1287857, 2024.

[13] Graeme J Hankey. Stroke. *The Lancet*, 389(10069):641–654, 2017.

[14] Owen Hellum, Christopher Steele, and Yiming Xiao. Sonia: an immersive customizable virtual reality system for the education and exploration of brain networks. *Frontiers in Virtual Reality*, 4, 2024.

[15] Dylan J H A Henssen, Loes van den Heuvel, Guido De Jong, Marc A T M Vorstenbosch, Anne-Marie van Cappellen van Walsum, Marianne M Van den Hurk, Jan G M Kooloos, and Ronald H M A Bartels. Neuroanatomy learning: Augmented reality vs. cross-sections. *Anatomical sciences education*, 13(3):353—365, May 2020.

[16] Andrew Ho. Evaluating data and learning rates, 2019.

[17] Sebastian Ille, Ann-Katrin Ohlerth, David Colle, Henry Colle, Olga Dragoy, John Goodden, Pierre Robe, Adrià Rofes, Emmanuel Mandonnet, Erik Robert, Djaina Satoer, Catarina Pessanha Viegas, Evy Visch-Brink, Martine van Zandvoort, and Sandro M. Krieg. Augmented reality for the virtual dissection of white matter pathways. *Acta Neurochirurgica*, 163:895–903, April 2021.

[18] Anand A. Joshi, Soyoung Choi, Yijun Liu, Minqi Chong, Gaurav Sonkar, Jorge Gonzalez-Martinez, Dileep Nair, Jessica L. Wisnowski, Justin P. Haldar, David W. Shattuck, Hanna Damasio, and Richard M. Leahy. A hybrid high-resolution anatomical mri atlas with sub-parcellation of cortical gyri using resting fmri. *Journal of Neuroscience Methods*, 374:109566, 2022.

[19] Georgios Lampropoulos, Vassilis Barkoukis, Kevin Burden, and Theofylaktos Anastasiadis. 360-degree video in education: An overview and a comparative social media data analysis of the last decade. *Smart Learning Environments*, 8, 09 2021.

[20] Chin Fu Liu, Johnny Hsu, Xin Xu, Ganghyun Kim, Shannon M. Sheppard, Erin L. Meier, Michael I. Miller, Argye E. Hillis, and Andreia V. Faria. Digital 3d brain mri arterial territories atlas. *Scientific Data*, 10(1), December 2023. Publisher Copyright: © 2023, The Author(s).

[21] Marcus Lopez, Megan Ward, Taku Komura, and Juliette Gall. Vr neuroanatomy: Enhancing education through interactive learning. *Medical Education*, 55(2):149–158, 2021.

[22] Magdalena Mendez-Lopez, M. Carmen Juan, Ramon Molla, and Camino Fidalgo. Evaluation of an augmented reality application for learning neuroanatomy in psychology. *Anatomical Sciences Education*, 15(3):535–551, 2022.

[23] Meta. The difference between vr, ar, and mr, 2023. Accessed: 2024-06-26.

[24] Tadatsugu Morimoto, Takaomi Kobayashi, Hirohito Hirata, Koji Otani, Maki Sugimoto, Masatsugu Tsukamoto, Tomohito Yoshihara, Masaya Ueno, and Masaaki Mawatari. Xr (extended reality: Virtual reality, augmented reality, mixed reality) technology in spine medicine: Status quo and quo vadis. *Journal of Clinical Medicine*, 11(2), 2022.

[25] Christian Moro, Jessica Smith, and Emma Finch. Improving stroke education with augmented reality: A randomized control trial. *Computers and Education Open*, 2:100032, 2021.

[26] Christian Moro, Zane Štromberga, Athanasios Raikos, and Allan Stirling. The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education*, 10(6):549–559, 2017.

[27] Yanyu Mu, David Hocking, Zhan Tao Wang, Gregory J Garvin, Roy Eagleson, and Terry M Peters. Augmented reality simulator for ultrasound-guided percutaneous renal access. *International journal of computer assisted radiology and surgery*, 15:749–757, 2020.

[28] National Heart, Lung, and Blood Institute. What is a stroke?, 2023. Accessed on: July 6, 2024.

[29] F.H. Netter. *Atlas of Human Anatomy*. Number no. 474 in Atlas of Human Anatomy. Saunders/Elsevier, 2006.

[30] William J. Powers, Alejandro A. Rabinstein, Teri Ackerson, Opeolu M. Adeoye, Nicholas C. Bambakidis, Kyra Becker, José Biller, Michael Brown, Bart M. Demaerschalk, Brian Hoh, Edward C. Jauch, Chelsea S. Kidwell, Thabele M. Leslie-Mazwi, Bruce Ovbiagele, Phillip A. Scott, Kevin N. Sheth, Andrew M. Southerland, Deborah V. Summers, and David L. Tirschwell. 2018 guidelines for the early management of patients with acute ischemic stroke: A guideline for healthcare professionals from the american heart association/american stroke association. *Stroke*, 49(3):e46–e99, 2018.

[31] R. Rohkamm. *Color Atlas of Neurology*. Clinical sciences. Thieme, 2004.

[32] Jeff Sauro and James R. Lewis. *Quantifying the User Experience, Second Edition: Practical Statistics for User Research*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2nd edition, 2016.

[33] Daniel Souza, Rafael Nascimento, Thiago Silva, and Flavia Borges. Vr-based anatomical puzzle game for neuroanatomy education: Design and evaluation. *Anatomical Sciences Education*, 14(1):23–34, 2021.

[34] Katarzyna Stepan, Adam Dunn, Andrew Vande Moere, Markus Tönnis, and Roland Kockro. Neuroanatomy learning: Augmented reality vs. cross-sections. *Journal of Neurosurgery*, 126(3):586–594, 2017.

[35] UniteAR. Difference between augmented reality and virtual reality, 2023. Accessed: 2024-06-26.

[36] Christian Wagner and Lili Liu. *Creating Immersive LearningImmersive learning Experiences: A Pedagogical Design Perspective*, pages 71–87. Springer International Publishing, Cham, 2021.

[37] Yiming Xiao, Simon Drouin, Ian J. Gerard, Vladimir S Fonov, Bérengère Aubert-Broche, Yuhan Ma, Marta Kersten-Oertel, Donatella Tampieri, and D. Louis Collins. An augmented-reality system prototype for guiding transcranial doppler ultrasound examination. *Multimedia Tools and Applications*, 77:27789 – 27805, 2018.

[38] Xuanhui Xu, Eleni Mangina, and Abraham G. Campbell. Hmd-based virtual and augmented reality in medical education: A systematic review. *Frontiers in Virtual Reality*, 2, 2021.

[39] Kaissar Yammine and Claudio Violato. A meta-analysis of the educational effectiveness of three-dimensional visualization technologies in teaching anatomy. *Anatomical Sciences Education*, 8(6):525–538, 2015.

[40] Jiakai Zhang, Gege Li, Qinglin Huang, Qinna Feng, and Heng Luo. Augmented reality in k–12 education: A systematic review and meta-analysis of the literature from 2000 to 2020. *Sustainability*, 14(15), 2022.