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# A Framework for Mixed Reality within Healthcare Education

A Thesis by Benyamin Ebadinia

Submitted to the Graduate Faculty of the Saint Mary's University in partial fulfillment of the requirements for the degree of Master of Science in Software Engineering

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# Abstract

Understanding complex three-dimensional systems and spatial relationships is a recurring difficulty in healthcare education, where students are often expected to reason about internal structures and multi-system processes from 2D diagrams, textbook figures, and static mannequins. This thesis presents the design, implementation, and mixed-methods evaluation of *Systems Simulation*, a reusable mixed reality (MR) application intended to help undergraduate nursing students explore human anatomy and pathophysiology using immersive 3D visualization.

Built in C# with the StereoKit framework for Microsoft HoloLens 2, *Systems Simulation* organizes nine anatomical body systems within a shared application. Learners can select a system, anchor the model in their physical space, move around it, and manipulate the 3D view while observing simple animations such as a beating heart or diaphragm motion. The architecture separates content from interaction logic and provides a repeatable workflow for importing and aligning 3D models, enabling additional systems to be incorporated without redesigning the overall interface.

To examine how this framework functions in practice, the prototype was deployed in an undergraduate Introduction to Pathophysiology course at St. Mary's University. Thirteen students from the course volunteered to participate; eight completed the full study sequence and were included in the analysis. Each participant completed a paper-based short-answer anatomy test, an MR-based short-answer test targeting the same underlying concepts, a Likert-scale survey about understanding, spatial relationships, engagement, usability, and future applications, and a brief set of reflection questions. Sessions were audio- and video-recorded, and the resulting quantitative and qualitative data were analyzed using a mixed-methods approach.

Across the eight participants with complete data, total accuracy scores were slightly higher in the MR condition: the mean paper-based score was 19.25 out of 24, compared to 20.19 on the MR-based test, with six of the eight students scoring higher in MR and two scoring lower. Likert-scale responses indicated that students found the mixed reality session engaging and helpful for visualizing anatomical structures and spatial relationships, while also revealing some friction with hand tracking and interface controls. Thematic analysis yielded five recurring themes—Spatial Understanding and 3D Relationships, Engagement and Motivation, Perceived Learning and Confidence, Usability and Interaction, and Future Nursing Applications/Feature Improvements—which together describe how students experienced the MR anatomy prototype and how they imagined extending it to real nursing tasks, simulation scenarios, and patient education.

Overall, the results suggest that a reusable mixed reality framework like *Systems Simulation* can support nursing students' spatial reasoning, engagement, and perceived learning while highlighting design considerations for making MR a reliable, non-disruptive part of routine study. The thesis concludes by outlining how the same architecture and design principles could be extended to additional healthcare scenarios and future engineering case studies that require understanding of complex three-dimensional systems.

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# List of Abbreviations

| | |
|---|---|
| AR | Augmented Reality |
| MR | Mixed Reality |
| VR | Virtual Reality |
| XR | Extended Reality |
| AV | Augmented Virtuality |
| HMD | Head Mounted Displays |
| 3D | Three-Dimensional |
| UI | User Interface |
| UX | User Experience |
| STEM | Science; Technology; Engineering; Mathematics |
| HCD | Human-Centered Design |
| K-12 | Kindergarten to 12th Grade |

# Chapter 1 – Introduction

Across STEM education, students are routinely asked to reason about three-dimensional structures and dynamic processes, yet most of their instructional materials remain two-dimensional: static diagrams, lecture slides, and physical models with fixed views. When learners cannot move around a model, change its scale, or see how structures relate in depth, their mental models of complex systems can remain incomplete and difficult to comprehend. This thesis investigates Mixed Reality (MR) as a medium for supporting more interactive and immersive learning experiences within healthcare education while also developing a broader framework to enhance spatial learning across disciplines.

Mixed Reality technologies, which blend digital content with the physical environment, have become increasingly accessible through head-mounted displays and related tools. In clinical and educational settings, MR and other XR systems have already shown promise for visualizing complex anatomy, simulating procedures, and providing more intuitive views of structures that are not directly visible. However, many existing MR applications in healthcare are single-purpose tools tied to a specific procedure, topic, or device, and relatively few are documented as reusable frameworks that can be adapted across multiple courses or learning objectives. In typical classroom settings, there is still limited empirical evidence on how MR-based learning experiences compare to traditional materials for nursing students who must master foundational healthcare content.

In this thesis, I address that gap by designing a framework for using Mixed Reality in healthcare that is implemented and evaluated through an MR anatomy prototype for undergraduate nursing students. Working with faculty in Nursing, Life Sciences, and Exercise Science, I identified recurring instructional needs, especially around helping students visualize spatial relationships and dynamic systems in human body structures. I then translated these needs into use cases for a mixed reality learning platform and into the central research questions for this thesis. Based on these needs, I formulated the following research questions for this thesis:

1. *Research Question 1 (Learning Outcomes):* How does a reusable Mixed Reality framework support undergraduate nursing students' learning of anatomical systems compared to traditional paper-based instructional materials?

2. *Research Question 2 (Perceptions and UX):* What are undergraduate nursing students' perceptions of engagement, usability, spatial understanding, and perceived confidence when learning anatomy through the Mixed Reality prototype versus traditional materials?

3. *Research Question 3 (Design Principles):* What design principles enable a Mixed Reality anatomy application to be reusable, modular, and effective for healthcare education?

To answer these questions, I use a mixed-methods evaluation that combines short-answer assessments given on paper and within the MR session, Likert-scale survey items on understanding, engagement, and usability, as well as open-ended reflections about students' experiences. In turn, the data is used to examine how nursing students' learning experiences differ when they engage with traditional paper-based materials versus an MR-based simulation, and what design lessons emerge for future MR tools in healthcare education.

The remainder of this thesis is organized as follows. In Chapter 2, I survey prior work on Mixed Reality, including core definitions, historical developments, current applications in multiple domains, and end it by identifying gaps and opportunities that motivate this thesis. In Chapter 3, I describe the stakeholder interviews and requirements-gathering process that shaped the design of the MR framework for healthcare education. In Chapter 4, I present an overview of the system and summarize its implementation, documenting the specific MR anatomy prototype used in the study. The study design and methodology, including participants, instruments, procedures, and analytic approach is detailed in Chapter 5. The quantitative and qualitative results of the mixed-methods evaluation are reported in Chapter 6. In Chapter 7, I discuss these results in relation to the research questions identified earlier and existing literature, highlighting design implications, limitations, and directions for future work. Finally, I conclude the thesis by summarizing the contributions and outlining how a framework-based approach to Mixed Reality can support ongoing innovation in healthcare education in Chapter 8.

# Chapter 2 - Survey of Mixed Reality

In this chapter, I provide background on mixed reality (MR) technologies, including what MR is, how it has developed over time, and how this technology is currently being used in entertainment, industry, education, and healthcare. This context is essential for understanding why MR is a promising medium for learning and how existing work grounds the design of the platform developed in this thesis.

## 2.1. Mixed Reality Taxonomy

Mixed Reality (MR) refers to systems that blend real and virtual environments. Milgram and Kishino (1994) define MR as the merging of “real” and “virtual” worlds along a virtuality continuum. In practice, an MR display is meant to present real and computer-generated objects together in a single view [*40*].

There can be many implementations for this technology even within the same industry. For example, in medical contexts, MR can be used to overlay virtual anatomical models onto a patient while still showing the patient’s body or conversely insert live video of a patient into a mostly virtual scene. In each case the real and virtual elements coexist and interact in real time within a single view. To support this definition, Azuma (1997) characterizes AR-like systems (specifically AR systems) by three core features: they combine real and virtual content, operate interactively in real time, and register the virtual content in 3D [*8*]. These criteria capture the essence of any MR experience.

MR is thus often described as a superset concept that includes AR and VR, however, these three technologies occupy different points on the reality–virtuality spectrum. In VR, the user is completely immersed in a synthetic environment where the system replaces the real world entirely with computer-generated 3D content [*40*]. VR displays block or ignore the real world, simulating scenes that may mimic reality or be purely fictional. By contrast, AR supplements the real world rather than replaces it. Azuma (1997) defines AR as allowing the user to see the real world with virtual objects superimposed on it [*8*]. In AR, the physical surroundings remain visible, and the digital augmentations appear to coexist in the same space. Milgram and Kishino (1994) similarly describe AR as a real environment that is "augmented by means of virtual (computer graphic) objects," meaning real scene plus virtual overlays [*40*].

Mixed Reality encompasses both of these and everything in between. An MR display might be more like AR, VR, or as a hybrid of the two. By this account, MR simply refers to any hybrid display between these two concepts [*40*]. In short, MR systems aim to extend the user's perception by integrating digital information into the real world (or vice versa) without fully detaching them from physical reality.

## 2.2. History of Mixed Reality

The origin of MR goes back to the 1950s and 1960s, when researchers built the first immersive simulators. For example, Morton Heilig's 1957 Sensorama enabled 3D stereo films with motion and scent, demonstrating early multisensory immersion. In 1966, Ivan Sutherland created the "Sword of Damocles," the first head-mounted display, which could superimpose simple computer graphics onto the user's view of the real world [*7*]. Although primitive, these devices demonstrated the possibility of overlaying virtual imagery on reality.

The term Virtual Reality (VR) was popularized in the 1980s by Jaron Lanier, who developed early glove-and-goggle systems aimed at full immersion [*2*]. In 1992, Boeing researcher Thomas Caudell coined the term Augmented Reality (AR) to describe a system for overlaying wiring diagrams onto real machinery [*28*]. A few years later, Milgram and Kishino (1994) explicitly proposed the mixed-reality continuum and taxonomies. They classified various display systems into several hybrid types and introduced "Augmented Virtuality" alongside AR as complementary cases [*40*]. This work formalized MR as a distinct concept and helped categorize the many systems that combine real and virtual elements.

Since the 1990s, hardware advances and the widespread availability of the internet have accelerated MR's development. In the 2010s and 2020s, MR technology matured with devices such as the Microsoft HoloLens and AR-capable smartphones [*7*]. Recent surveys note that 5G/6G wireless networks and the Internet of Things (IoT) are being harnessed to enable real-time interaction between real and virtual worlds in increasingly complex environments (Adil et al., 2024) [*2*]. Today, emerging metaverse devices such as the Meta Quest family aim to link VR, AR and MR shared, persistent digital spaces.

## 2.3. Applications of AR in Different Domains

Although I mainly focus on applications of AR and MR in healthcare and nursing education in this thesis, it is important to understand how these technologies are being used in other fields. In particular, how AR has been applied in entertainment and gaming, industry training and engineering education, and general education is briefly reviewed in this section.

### 2.3.1. Entertainment/Gaming

Augmented Reality is increasingly being used to enhance engagement and learning through interactive and immersive gaming environments in entertainment and educational settings. One notable example is the mobile AR game Pokémon GO, which has been shown to increase physical activity, promote outdoor exploration, and stimulate social interaction among players (Lee et al., 2021) [*29*]. The game's location-based mechanics and integration with real-world locations create opportunities for exercise and social connection, especially among adolescents and young adults. Complementing this, a focused review of educational AR games highlights that such applications can support motivation, cognitive development, and knowledge retention by allowing learning to take place in an immersive environment (Amanatidis, 2022) [*5*]. These AR games have been successfully applied to subjects ranging from environmental science to creative writing, encouraging subject matter understanding and problem-solving skills.

### 2.3.2. Industry Training and Engineering Education

In industrial settings, AR has proven beneficial for real-time task assistance and workforce training. For example, Boeing’s adoption of extended reality (XR) technologies on its production floors to enable technicians to superimpose detailed 3D schematics directly onto complex assemblies has reduced assembly errors and expedited inspection cycles by up to 25% (Laughlin, 2018) [*28*].

More broadly, a recent qualitative meta-analysis of AR implementations in Industry 4.0 environments found that AR systems enhance operational efficiency and operator competence through the use of AR-guided instructions and interactive simulations, leading to decreased task completion times, reduced cognitive load during maintenance procedures, and improved knowledge retention in training scenarios (Morales Méndez & del Cerro Velázquez, 2024) [*42*].

Beyond manufacturing, AR has also been incorporated into university-level engineering education to help students understand complex 3D content and systems. Girbacia and Butnariu (2012) developed a markerless AR “book” for an undergraduate Theory of Mechanisms and

Machines course, in which virtual 3D mechanism models are co-located with the corresponding textbook pages so that students can see simulations of structure and kinematics directly on the printed diagrams. The authors argue that this low-cost desktop AR setup offers an intuitive way for inexperienced learners to study mechanism simulation without relying on expensive physical installations, though they do not report a formal comparative evaluation of learning outcomes (Girbacia & Butnariu, 2012) [*22*].

Civil engineering courses show comparable patterns. Miner et al. (2025) developed an AR tool that projects structural models onto real campus buildings, and students using this system achieved higher average gains on conceptual quizzes about structural behavior than those relying on conventional instruction [*41*]. Other disciplines mirror these benefits. Lucas et al. (2018) describe an AR circuit simulator in which electrical engineering students assemble token-based circuits and see real-time simulated currents and voltages, which students felt made abstract circuit behavior more intuitive and engaging [*30*]. Rebello et al. (2024) synthesize multiple studies in chemical engineering where AR visualizations of otherwise invisible processes and process equipment are used to help learners understand internal dynamics and practice operating pilot-plant systems more confidently [*46*]. Together, these studies suggest that AR can support industrial training and engineering education by improving spatial reasoning, conceptual understanding of complex systems, and learner engagement across multiple engineering domains.

### 2.3.3. General Education

Beyond entertainment and engineering contexts, AR has been widely explored as tools for general education across K–12 and higher education. Systematic reviews by Bacca et al.

(2014) and Akçayır and Akçayır (2017) extend this picture across primary, secondary, and university classrooms in subjects such as science, mathematics, language learning, and the arts. Many of the studies they examined reported improved learning gains and heightened motivation, along with increased interaction and collaboration, as students used AR to explore abstract or complex ideas in more concrete and engaging ways [*9*][*4*].

More recent reviews focusing on STEM subjects similarly find that AR can help learners at multiple grade levels visualize difficult science and mathematics concepts, often leading to gains in conceptual knowledge, enjoyment, and interest in STEM subjects (Ajit, 2020) [*3*]. Quantitative syntheses reinforce these qualitative trends. Meta-analyses by Hunaepi et al. (2023) and Zhang et al.(2020) report statistically significant positive effects of AR on student learning outcomes, with large effect sizes for achievement and performance measures across the studies they analyze [*26*][*55*].

At the same time, these reviews emphasize recurring challenges for classroom integration, including device and tracking limitations, software bugs and usability issues, the risk of cognitive overload or distraction when interfaces are poorly designed, and the need for teacher preparation and additional class time. They also highlight the importance of aligning AR activities with curricular goals rather than relying solely on the novelty of the technology (Bacca et al., 2014; Akçayır & Akçayır, 2017; Ajit, 2020; Zhang et al., 2022) [*9*][*4*][*3*][*55*]. Taken together, the general education literature suggests that when AR and MR experiences are carefully designed and supported, they can improve engagement and conceptual understanding across diverse subjects and age groups, highlighting their potential as a medium for teaching complex content.

## 2.4. Current Applications for MR in Healthcare

The current application of Mixed Reality across different domains of healthcare is presented in this section. Understanding these implementations is important for aligning the goals of this thesis within existing medical, educational, and training uses of MR technologies.

### 2.4.1. Patient Care

MR and AR are already being applied to enhance diagnostic processes and remote consultations. For example, Zimmer Biomet's OptiVu platform uses the HoloLens to create holographic patient visuals, enabling "doctors and patients [to] replicate realistic consultations, personalized care, treatment, and diagnosis" (Bansal et al., 2022) [*10*]. In practice, a patient can have imaging data (e.g. MRI or CT) overlaid onto their body or meet virtually with specialists who can view and manipulate 3D scans. Such systems can bridge patient–doctor gaps, reduce the need for patient travel (especially in rural areas), and support more informed decision-making.

MR has also shown promise in mental health treatment. XR headsets can simulate therapeutic experiences under clinician control. For instance, VR exposure therapy (VRET) has been used to successfully treated phobias by allowing patients to confront fear-inducing stimuli in a safe virtual setting (Bansal et al., 2022). Similarly, VR environments have been used to treat anxiety and PTSD by immersing patients in controlled scenarios. These immersive therapies are adjustable in real time and avoid actual harm, making them effective for psychological interventions [*10*].

### 2.4.2. Prosthetics

Mixed reality has been applied to help amputees train and adapt to prosthetic limbs. Early work by Anderson and Bischof (2012) introduced an AR "ARM Trainer" that overlays a virtual limb onto the user's body to guide myoelectric control. Although this study found no statistical difference in muscle control outcomes, it demonstrated that AR could provide an interface for practicing prosthesis movements and address psychological needs (e.g. phantom limb pain and self-image) during training [*6*].

More recent research has explored game-like and feedback-based prosthetic training using MR. For example, Deus (2023) developed AR game (ARm-Strong) in which non-amputees use a bypass prosthesis to perform virtual tasks; participants showed improvements in motor control during training [*16*]. Inglis and Blustein (2024) implemented a HoloLens-based app that overlays a color-coded visual indicator of grip force onto an upper-limb prosthesis, highlighting how MR can give real-time feedback to prosthesis users [*27*]. Such AR visualizations may help users fine-tune control that is often very complex and unintuitive with myoelectric limbs.

Other MR approaches address prosthetic-related therapy. For instance, Yeung et al. (2021) report that VR treatment of phantom pain shows promising results in case studies by providing the illusion of a restored limb which allows patients to "move" and feel their missing limb in ways that have been associated with reduced pain [*53*].

### 2.4.3. Operational Assistance

MR is also rapidly transforming surgical practice preoperatively and in the operating room. For pre-operations, AR is being used to overlay 3D anatomical scans onto the patient model, allowing a surgeon to trace incision lines or probe tumor boundaries with high precision.

Cutolo et al. (2020) describes an AR headset framework for guided surgery where medical images are registered in real time; their tests on a simulated incision task achieved sub-millimeter accuracy, indicating AR's potential for precise surgical guidance [*14*].

Within the operating room, MR devices give surgeons a way to visualize structures that are not easily visible through conventional imaging alone. For example, researchers at the Cleveland Clinic trialed a HoloLens system for liver tumor ablation in which they overlayed a 3D holographic image of the patient's tumor and vessels onto the patient during the procedure. This allowed the physician to see the tumor in situ and plan the needle trajectory directly on the patient, improving visualization beyond standard 2D imaging (Cleveland Clinic, 2019) [*13*]. Similar systems are being explored for neurosurgery and other surgical specialties where accurate spatial registration and intuitive visualization are critical.

### 2.4.4. Education

Beyond physical patient care, MR and AR are important educational tools in health professions. Studies have shown that VR-based surgical training improves technical skills and can reduce intraoperative errors. For example, laparoscopic surgeons who train in VR achieve faster proficiency than those using standard methods (Yeung et al., 2021) [*53*].

Outside of an operational setting, interactive 3D models and simulations can also help students learn complex biomedical concepts more effectively. Surveys of AR in education report that AR educational applications can significantly boost engagement and learning performance when integrated into well-designed lessons. Zulfiqar et al. (2023) note that AR features engage students and help instructors explain complex topics more clearly [*56*]. Within medical and nursing education, these capabilities suggest that MR platforms can support active, spatially grounded learning experiences that complement traditional lectures and 2D materials.

## 2.5. Gaps and Opportunities

The literature reviewed in this chapter shows that AR and MR have been widely explored across multiple education levels and engineering disciplines, where they can improve engagement, motivation, and conceptual understanding of complex or abstract concepts. In healthcare, MR and AR are already used for patient care, prosthetic training, surgical planning, and professional education, demonstrating clear benefits for visualization and safe practice in clinical and training contexts.

At the same time, the work surveyed here tends to focus on single-purpose applications tailored to specific procedures, devices, or individual topics. These are often implemented as standalone prototypes rather than modular, reusable frameworks that can support multiple systems. Within the studies summarized in Sections 2.3 and 2.4, there is little emphasis on MR platforms designed specifically for nursing students who need to recall anatomy and physiology for their current coursework, or on mixed-methods evaluations that combine paper-based assessments, in-headset tasks, Likert-scale measures, and qualitative reflections around the same MR experience. There is also limited discussion of MR architectures that are explicitly designed to be extensible across domains, such as from healthcare education into engineering or other STEM areas. These gaps motivate the design and evaluation of a modular MR learning platform that targets complex healthcare content for nursing students while remaining reusable for other technical disciplines.

# Chapter 3 - Stakeholder Needs and Requirements Gathering

Within this chapter, I will be going over the multiple discussions that occurred between my advisor, Dr. Özgür Aktunç, and me with the Exercise Science, Life-Sciences, and Nursing departments. These conversations were vital in gathering requirements and developing the foundation for my prototype.

## 3.1. Exercise Science

In late March 2025, we met with Dr. Gary Guerra, Professor of Exercise Science at St. Mary's University, in the Human-Centered Design Lab to discuss potential mixed reality use cases in his domain. After I demonstrated the Microsoft HoloLens 2, Dr. Guerra immediately focused on how this technology could support patients who are adapting to new prosthetic devices. He described how many of his patients struggle with motor control and confidence during early rehabilitation, and he proposed using mixed reality to create structured practice scenarios that would make these early stages more guided and engaging.

From this discussion, we developed the idea of a prosthetic-assistance application that would allow individuals with physical disabilities to rehearse everyday tasks in a safe, simulated environment. Example tasks included answering a phone, turning off lights, or performing other routine movements that are functionally important but difficult to practice consistently in a clinic.

Dr. Guerra also suggested using three-dimensional models of prosthetic limbs to help patients visualize an artificial limb on their own body before surgery or fitting. In his view, being able to see how the device would look and move in relation to their existing anatomy could support psychological adjustment. Shortly after our meeting, he shared prior research and several

3D scans of relevant body parts that could be brought into a mixed reality environment as reference models.

## 3.2. Life-Sciences

In early March 2025 we met with Dr. Thomas Macrini, Dean of the School of Engineering and Technology at St. Mary's University, in the anatomy lab that houses the Anatomage table. The purpose of this meeting was to give me a deeper understanding of how the Anatomage table is currently used in Anatomy teaching, and to introduce Dr. Macrini to the capabilities of the Microsoft HoloLens 2. During the session, we decided to record a short lecture from his point of view using a 3D painting application on the HoloLens, allowing him to annotate key regions directly over the digital cadaver displayed on the Anatomage table as he explained anatomical structures to an imagined class (Figure 3.1). This demonstration explored the feasibility of using mixed reality as a virtual teaching aid layered on top of an existing tool.

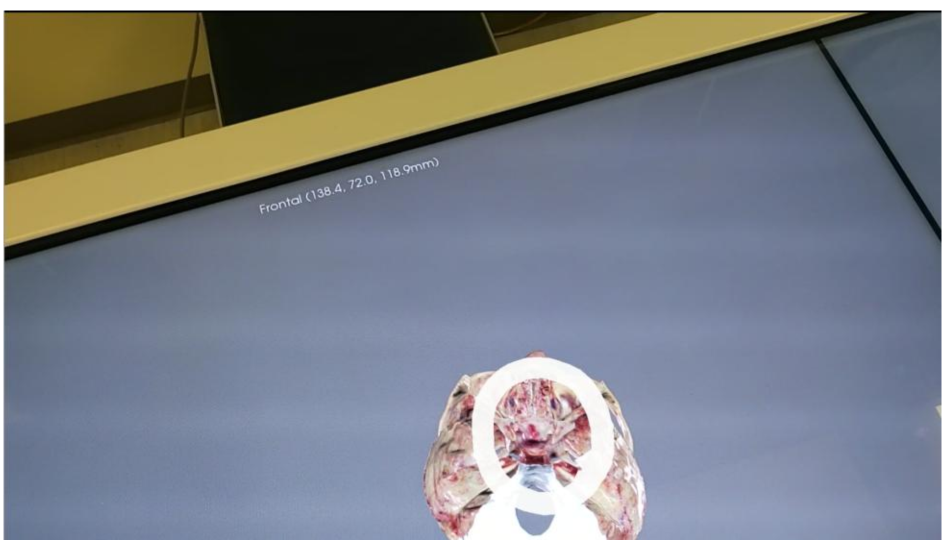


***Figure 3.1:*** *Anatomage table lecture using AR painting on Microsoft HoloLens 2.*

In our discussion after the recording, Dr. Macrini emphasized that mixed reality would be most useful as a complementary tool rather than a replacement for the Anatomage table. He was particularly interested in the potential for MR to support dynamic annotation and three-dimensional exploration around the table. For example, highlighting structures in midair, tracing paths between related organs, or pulling out individual components for closer inspection while still grounding the lesson in the familiar Anatomage table lecture. These ideas led to the recommendation that 3D models of anatomical parts could be used as a supplementary aid to the Anatomage table, giving students multiple ways to view and interact with the same underlying anatomy.

## 3.3. Nursing

Our first meeting with the Nursing department was in late February 2025 with Dr. Donna Badowski, the Vice Dean of the School of Science, Engineering, and Technology and Founding Director of Nursing at St. Mary's University. We met in her office on the third floor of the Blank–Sheppard Innovation Center. After some initial introductions, I gave a short demonstration of a simple painting application on the Microsoft HoloLens 2 and showed a wireframe of a sample patient interface that I had sketched as an early concept for the project. This mockup illustrated how basic patient information and vital signs might be displayed in mixed reality (Figure 3.2).

During this conversation, Dr. Badowski explained that what would be most helpful for Nursing was not a standalone MR charting interface, but a tool that could overlay virtual elements onto their existing Laerdal Simulator mannequins (Figure 3.3). She described how such an AR/MR tool could be used to demonstrate clinical signs that the physical mannequins cannot currently show, such as pitting edema or jaundice, by rendering these features holographically on top of the mannequin. This would allow nursing instructors to create richer simulation scenarios while continuing to use the equipment that students already know.


***Figure 3.2:*** *Wireframe of sample patient interface*

A second meeting with the Nursing department took place in mid-April 2025 with Dr. Badowski and Professor Eloisa Garza in a conference room on the third floor of the Blank–Sheppard Innovation Center. This meeting was more focused on concrete use cases that Nursing faculty wanted to address with mixed reality. Professor Garza emphasized the need for a tool that would help students visualize what is happening inside the body while they are assessing a patient, connecting textbook descriptions of pathophysiology to observable signs and symptoms at the bedside. She gave examples such as cardiovascular diseases like hypertension and clogged arteries, and neurological disorders such as seizures and migraines, where students often struggle to link abstract mechanisms to what they observe in practice. She also suggested that mixed reality could potentially be used to simulate some of the difficult conversations that nurses have with family members of patients by using holographic people to represent the family in these scenarios.

***Figure 3.3:*** *Laerdal Simulator mannequin*

Over the following summer, I reviewed the Nursing curriculum, with a particular focus on Professor Garza's *Introduction to Pathophysiology* course. Based on this curriculum review, I designed an initial anatomy and pathophysiology prototype that aligned with the systems and conditions covered in her course. The course was taught using Lippincott CoursePoint [*43*] and followed a flipped-classroom format in which students completed readings and online modules before coming to class, then used class time to review and apply what they had learned. Because

Fall 2025 was the first semester of the new Nursing program at St. Mary's, this *Intro to Pathophysiology* class was the only Nursing course being offered, so there were no prior internal courses to use as reference points.

During the Fall 2025 semester, I met with Professor Garza multiple times to refine the prototype. I mirrored the unit layout of her *Intro to Pathophysiology* course so that the mixed reality content would track the progression of topics students were encountering in CoursePoint. In each meeting, I showed her updated versions of the anatomy prototype and incorporated her feedback on which systems, conditions, and visualizations would be most useful for first-semester Nursing students. She also provided specific questions that I later used to construct the paper-based and MR-based short-answer tests. I visited her class twice: once early in the semester to observe her teaching style and how students engaged with the flipped-classroom structure, and a second time later in the term to recruit volunteers for the mixed reality study.

Together, these three stakeholder groups shaped the design requirements for the mixed reality platform (Table 3.1). Building on prior work by Daftarian and Aktunç (2023) on screenless and spatial interfaces, I treated these requirements as constraints on how the interface and model logic should be organized, emphasizing flexible resizing, repositioning, and reuse across different MR learning modules [*15*]. These stakeholder-informed requirements and design principles guided the evaluation in Chapter 5 and the research questions addressed in Chapters 6 and 7.

| # | Requirement | Stakeholder | Status |
|---|---|---|---|
| 1 | Support safe and simulated practice of everyday functional tasks to build motor control and confidence. | Exercise Science | Out of scope for current MR anatomy prototype; provides use-case for future work. |
| 2 | Act as a complementary layer to existing tools, allowing instructors to keep familiar workflows. | Life Sciences | Conceptually addressed; current study uses MR alongside traditional materials rather than directly integrated with Anatomage hardware. |
| 3 | Enable dynamic annotation and highlighting of anatomical regions during instruction. | Life Sciences | Out of scope for current MR anatomy prototype; provides use-case for future work. |
| 4 | Support 3D exploration while maintaining orientation. | Life Sciences | Implemented in the MR anatomy prototype via fixing models to room. |
| 5 | Overlay virtual clinical diagnoses on simulator mannequins to show findings they cannot physically display. | Nursing | Out of scope for current MR anatomy prototype; provides use-case for future work. |
| 6 | Help students visualize what is happening inside the body while assessing a patient, linking pathophysiology mechanisms to observable signs and symptoms. | Nursing | Out of scope for current MR anatomy prototype; provides use-case for future work. |
| 7 | Align MR content with Intro to Pathophysiology course units and the systems students find conceptually challenging. | Nursing | Implemented in the MR anatomy prototype via the choice of the MR anatomy systems. |
| 8 | Provide a simple, low-friction interface appropriate for first-semester nursing students, avoiding unnecessary complexity. | Nursing | Implemented in the MR anatomy prototype via minimal UI, basic menus, and in-scene controls. |
| 9 | Be modular and reusable, treating individual body systems as plug-in modules that share a common interaction and UI layer. | Cross Discipline | Implemented in the software architecture. |
| 10 | Maintain a minimal, spatial UI that keeps learner attention on the models rather than on menus, supporting reduced cognitive load. | Cross Discipline | Implemented via minimal UI, basic menus, and in-scene controls. |
| 11 | Be hardware-agnostic where possible, separating content and interaction from device-specific details so the framework can extend beyond HoloLens 2. | Cross Discipline | Implemented in the software architecture. |

***Table 3.1:*** *System requirements derived from stakeholder meetings.*

# Chapter 4 - System Overview and Implementation Summary

In earlier chapters of this thesis, I introduced the motivation for using mixed reality in nursing education, reviewed relevant background work, and outlined the study design used to evaluate an MR-based learning experience. In this chapter, I build on that foundation and focus on the system that supports the study: the *Systems Simulation* mixed reality application. I first present a high-level overview of the platform and the rationale for the chosen hardware and software stack, then describe the tools and anatomical content used to construct the prototype. I then detail the software architecture that organizes scene management, interaction, content loading, and conclude with the implementation and authoring workflow used to add and adapt models. Together, these sections position the MR platform as a reusable framework that connects the conceptual motivations of the thesis with the empirical results presented in later chapters.

## 4.1. System Overview

The mixed reality platform developed for this study is an MR application for interactive exploration of complex spatial systems using the Microsoft HoloLens 2 and the StereoKit framework. Its primary goal is to provide a modular, reusable, and hardware-agnostic foundation that can support educational content across multiple domains. The initial implementation designed for this thesis illustrates this framework with human anatomy content for nursing education, enabling learners to explore selected body systems in mixed reality.

The HoloLens 2 (Figure 4.1) was selected as the target device for three main reasons. Practically, it was already available in the lab with existing institutional licenses, lowering deployment and setup overhead. Pedagogically, its hands-free, see-through design allows students to remain aware of their physical environment and move naturally while interacting with virtual content, which is important in clinical and skills-lab contexts. Experimentally, the nursing school had prior experience with VR headsets such as Meta Quest, but there were few examples of full AR-based implementations for nursing education; this project therefore also explores the potential of head-mounted AR for this setting. StereoKit was chosen as the application framework because it provides a lightweight, C#-based MR workflow that aligned with my existing skills and the project timeline, without requiring extensive prior graphics or game engine experience. In addition, StereoKit supports a hardware-agnostic architecture (ARM64), which is consistent with the goal of designing a framework that could be adapted to future XR devices beyond HoloLens 2.

***Figure 4.1:*** *Microsoft HoloLens 2 headset [44]*

The system is designed around a small set of core principles. Individual body systems are implemented as plug-in modules that all reuse the same interaction layer, so that new systems can be added without rewriting fundamental behaviors. The user interface is kept minimal and spatial, relying on simple menus and in-scene controls to reduce cognitive load and keep attention on the anatomy itself. The architecture is hardware-agnostic where possible, separating content and interaction logic from device-specific details. Finally, the framework is content-agnostic: while this thesis evaluates it with nursing anatomy, the same structure is intended to support healthcare and engineering learning modules. A high-level overview of these core components and their relationships is shown in Figure 4.2.

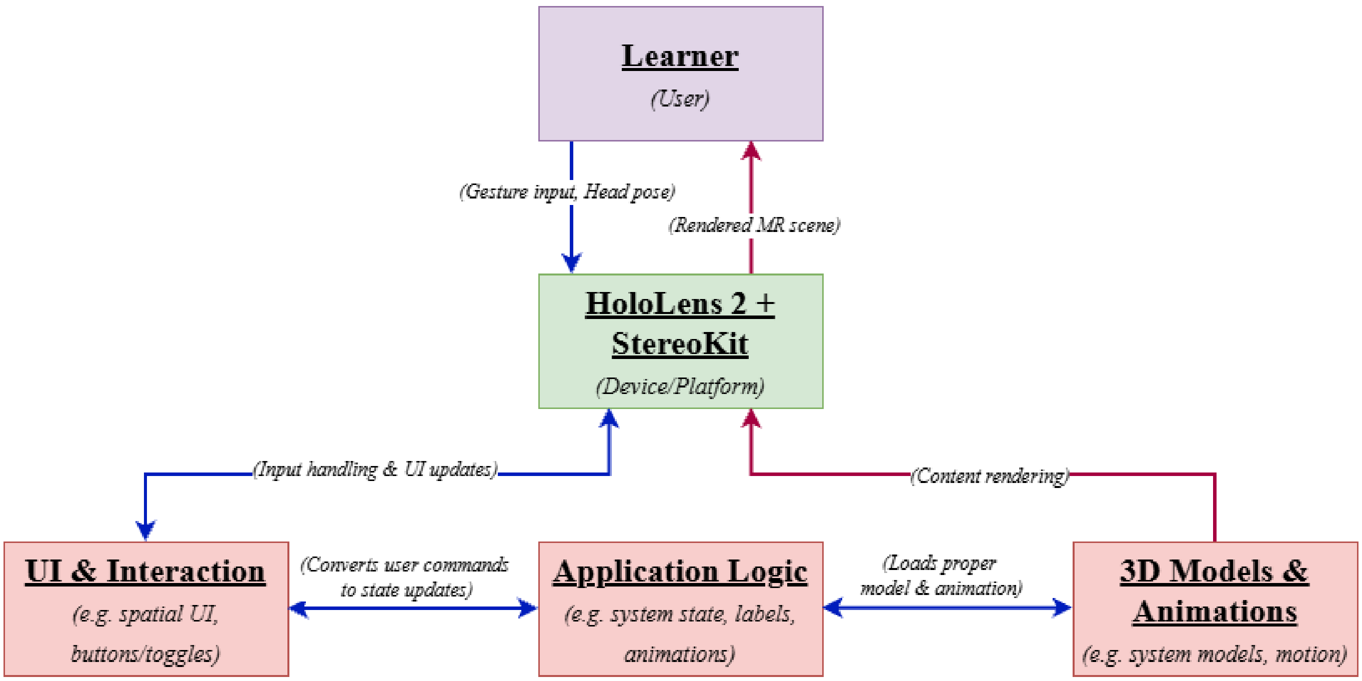


***Figure 4.2:*** *High-Level System Diagram*

## 4.2. Tools and Content Used for the Study

In this study, I used a combination of hardware, software, and web-based tools to develop and run the mixed reality prototype, capture study sessions, and prepare and analyze data. These tools can be grouped into four categories: (1) hardware used in the study, (2) mixed reality development, (3) 3D content preparation, and (4) study data analyzing. The anatomical content was assembled from freely available 3D assets and adapted to fit the mixed reality interaction model.

1. <u>Hardware used in the study</u>

   - *Microsoft HoloLens 2:* headset used to run the mixed reality prototype during all study sessions.
   - *Room camera:* recorded in-room sessions.
   - *iPhone 14 Pro:* captured audio of in-room sessions.
   - *External PC and monitor:* used to run the HoloLens desktop application to manage the HoloLens and mirror the HoloLens view during the tutorial so participants could see the mixed reality scene.
   - *Laptop:* used to read the script and questions, stop/start room recording, and take notes during data collection.

2. <u>Mixed reality development tools</u>

   - *StereoKit:* lightweight framework used for rendering, interaction, and animation on HoloLens 2.
   - *C# / .NET:* primary programming language and runtime for the mixed reality application.
   - *Visual Studio 2022:* integrated development environment used to build and deploy the StereoKit application to the HoloLens 2.
   - *Microsoft HoloLens Desktop Application:* used for device management, streaming the headset view to the external monitor, and capturing headset point-of-view.
   - *GitHub / GitHub Desktop:* version control platform used to manage code and asset revisions.
   - *gltfpack:* command-line tool used to optimize GLB models for real-time performance on HoloLens 2.

3. <u>3D content preparation tools</u>

   - *Sketchfab:* source of the free human anatomy models used as the basis for the body-system content in this study.
   - *Blender:* used to edit and clean meshes, adapt the downloaded models to the application's needs, and export GLTF assets compatible with StereoKit. The original Sketchfab assets included baked-in text labels; these labels were removed in Blender so that labeling could instead be controlled interactively through the mixed reality interface.

4. <u>Study data analyzation tools</u>

- *ChatGPT and NotebookLM:* used to generate initial automated transcripts from session audio, which were then manually revised and checked against the recordings.
- *Clipchamp:* used to put together and clean participant audio/video files prior to transcription.
- *Microsoft Excel:* used to record paper-based and MR-based test scores, organize A/B test versions, and compute basic descriptive statistics.
- *Microsoft Word:* used to design paper-based tests and surveys, volunteer forms, and printed study instructions.

All anatomical systems used in the study were drawn from free Sketchfab models by user "brianj.seely" [*48*] and then adapted in Blender. Systems were chosen because suitable free models were available and because each system corresponded directly to a unit in the *Introduction to Pathophysiology* course that participants were currently enrolled in. The final prototype included the following body systems:

- *Circulatory system:* shows a full-body arterial and venous network, with a simple beating-heart animation.
- *Digestive system:* shows the major organs involved in ingestion, digestion, and absorption.
- *Endocrine system:* shows the major hormone-secreting glands distributed across the body.
- *Lymphatic system:* shows lymphatic vessels and major lymph node groups.
- *Muscular system:* shows the major skeletal muscle groups of the trunk and limbs.
- Nervous system: shows the central and peripheral pathways throughout the body.
- *Respiratory system:* shows the gas-exchange structures involved in breathing, with a simple diaphragm animation.
- *Skeletal system:* shows major bones and skeletal structures.
- *Urinary system:* visualizes the structures within the excretory pathway.

A detailed list of anatomical structures included in each model, along with example screenshots, is provided in Appendix A. Together, these tools and content elements supported the development, deployment, and evaluation of the mixed reality framework within the context of an *Introduction to Pathophysiolog*y course.

## 4.3. Software Architecture

At the software level, the prototype is organized into four cooperating layers: (1) scene management for switching between the main menu and an active body system, (2) a UI and interaction layer that handles system selection, in-scene manipulation, and on-screen controls, (3) a content layer that loads models, animations, and label variants, and (4) a lightweight logging and debugging layer. The implementation is structured across a small set of C# classes (Program, AppState, SystemsModels, and LoadInterfaces), with the full source code provided in Appendix B.

### Scene Management Layer

Scene flow is coordinated in Program.Main using the StereoKit SK.Run loop. After initializing StereoKit and loading all models via SystemsModels.LoadAll(), the application tracks two main states: a flag indicating whether the main menu is visible (showUI) and an integer storing the last system selected (startButtonPressed). When showUI is true, the application calls LoadInterfaces.DrawStartInterface(), which displays the system selection menu and returns a numeric choice. A non-zero choice sets startButtonPressed, hides the menu, and resets AppState.Anchored so that the selected model and its controls can be anchored relative to the user on the next frame. When showUI is false, a switch on startButtonPressed selects the active model for drawing, using labeled or no-label variants based on AppState.ShowLabels. If the user presses the "Back" button in the model controls, LoadInterfaces.ModelInterface() returns true, which causes the loop to re-enable the main menu, clear the selection, and allow re-anchoring. Together, this logic implements simple scene management between a menu state and a per-system exploration state, as shown in the code excerpt below (Listing 4.1).

***Listing 4.1:*** *Core scene loop for menu and system states.*

```
bool showUI = true;
int  startButtonPressed = 0;

SK.Run(() =>
{
    if (showUI)
    {
        int choice = LoadInterfaces.DrawStartInterface();
        if (choice != 0)
        {
            startButtonPressed = choice;
            showUI             = false;
            AppState.Anchored  = false; // re-anchor model and UI next frame
        }
    }
    else
    {
       // Decide which model is active, and draw it
        Model? active = null;

        switch (startButtonPressed)
        {
           // Draw the circulatory system
            case 1:
                active = AppState.ShowLabels ?
                    SystemsModels.Circulatory : SystemsModels.CirculatoryNL;
                break;
            // ... cases 2-9 for other systems ...
        }

        // ... model placement, handle, and draw logic ...
    }
});
```

## UI and Interaction Layer

The UI and interaction layer combines menu-based choices with direct spatial manipulation by mapping user input events to application state and presenting them through StereoKit's built-in UI system. The main menu window, whose pose is stored in AppState.StartingWinPose, presents a welcome message and a vertical list of options, one for each body system the learner can explore. System selection is handled in DrawStartInterface() by a set of buttons such as UI.Button("Circulatory System"); pressing a button logs the event and sets an integer result (1–9) indicating the selected system, while leaving the result at 0 when no button is pressed in that frame. Once a system is active, LoadInterfaces.ModelInterface(Model model) provides a "Model Controls" window (with pose stored in AppState.ModelWinPose) that groups the in-app controls for the active system: a "Back" button to return to the home screen, a scale slider bound to AppState.SystemScale, animation controls (radio list, optional loop toggle, and "Play Selected" button) when animations are available, a "Labels" toggle bound to AppState.ShowLabels, and a "Reset Models" button that calls AppState.Reset(). Spatial manipulation of the 3D content itself is implemented using a StereoKit handle. The code constructs a bounding volume around the model and calls UI.Handle("system-handle", ref AppState.SystemPose, handleBounds), allowing the user to grab and reposition the system in space using hand tracking while the underlying AppState.SystemPose is updated.

From the learner's perspective, this interaction layer appears as a simple set of windows and controls inside the headset (Figures 4.3–4.5). The Starting Window (Main Window) presents a welcome message and a vertical list of buttons, allowing the student to choose which body system to explore (Figure 4.3). Once a system is selected, the corresponding anatomy model is anchored in front of the learner (Figure 4.4). Using the handle and scale slider, the student can reposition and rotate the model in three-dimensional space and adjust its size to move between a whole-body view and more detailed, organ-level inspection. A Labels toggle enables switching between labeled and no-label versions of the same model, controlling how much textual information is visible at once (Figure 4.5). For systems that include animations, additional controls in the Model Controls window allow the student to start, loop, and pause the available animation clips while viewing the model.

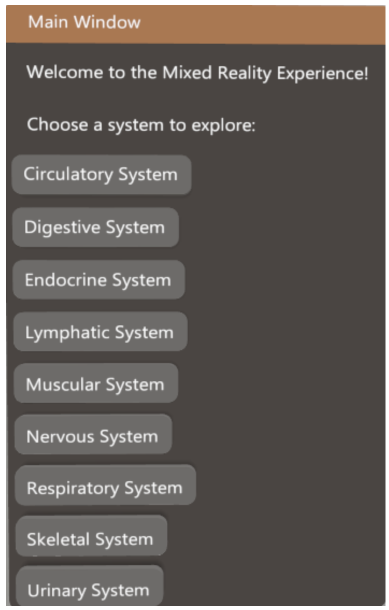


***Figure 4.3:*** *Systems Simulation main window for selecting a body system.*

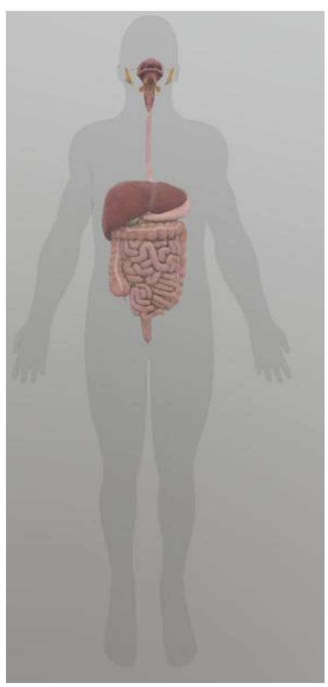

***Figure 4.4:*** *Digestive system model anchored in front of the learner.*

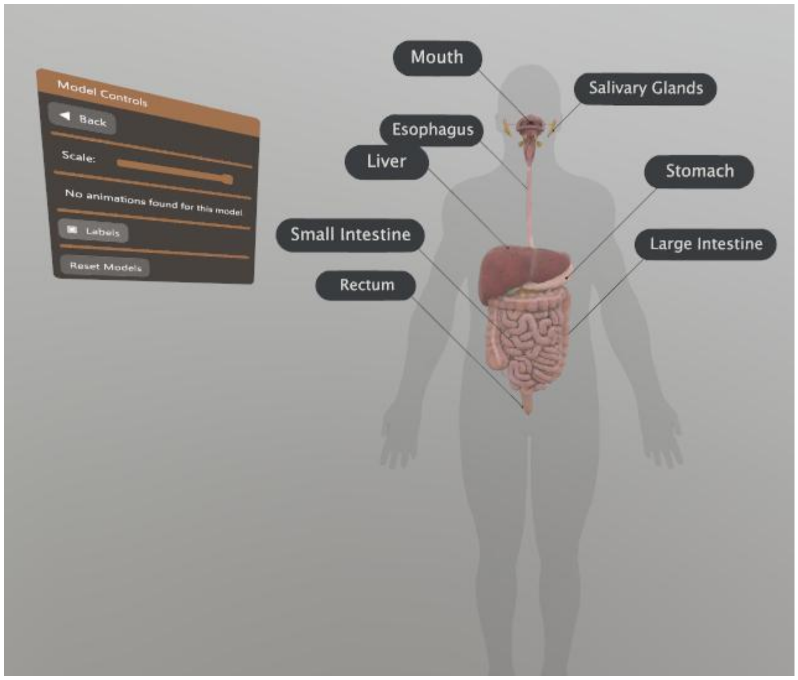


***Figure 4.5:*** *Digestive system model with labels and Model Controls window.*

**Content Layer**

All anatomy models and their label variants are encapsulated in the static SystemsModels class. The LoadAll() method loads one labeled and one no-label Model for each anatomical system from the 'Assets' directory. At runtime, Program chooses between each labeled and no-label Model pair based on the AppState.ShowLabels flag, so the same content layer supports labeled and unlabeled views without reloading assets. Simple model animations are enabled by calling TryPlayFirstAnimation(Model m, AnimMode mode) on the circulatory and respiratory models (and their no-label variants), which logs the available animation names and plays the first animation once to verify that animation data is present. Before deployment, the majority of models are saved as .opt.glb files that have been pre-optimized using gltfpack, reducing file size and draw calls for real-time performance on HoloLens 2. The LoadAll() methos is shown in the code excerpt below (Listing 4.2).

***Listing 4.2:****. Primary loading function for each model.*

```
public static void LoadAll()
{
    System.Diagnostics.Debug.WriteLine("Loading Models");

    Circulatory = Model.FromFile("circulatorySystem.glb");
    Digestive   = Model.FromFile("digestiveSystem.opt.glb");
    // ... other labeled models ...

    CirculatoryNL = Model.FromFile("circulatorySystemNL.glb");
    DigestiveNL   = Model.FromFile("digestiveSystemNL.opt.glb");
    // ... other no-label models ...

    TryPlayFirstAnimation(Circulatory,   AnimMode.Once);
    TryPlayFirstAnimation(CirculatoryNL, AnimMode.Once);
}
```

**Logging and Debugging Layer**

Logging and debugging are handled with simple System.Diagnostics.Debug.WriteLine statements that are active in development builds. These statements record button presses, track when models are loaded, and print information about available animations and skeletal model nodes. The TryPlayFirstAnimation function also logs each animation name before playing the first one, and additional debug code can traverse the skeletal model's node hierarchy to print node names and positions. No persistent logs or runtime analytics are stored; the logging layer is intended purely for developer-facing inspection while tuning model loading, animation behavior, and the per-system chest alignment configuration in AppState.

## 4.4. Prototype Implementation

The prototype application, *Systems Simulation*, was implemented as a reusable mixed reality framework that can display different anatomy systems while keeping the interaction pattern consistent. Although the current implementation focuses on human body systems, the underlying structure is intended to be general enough that future developers could adapt it to other domains, including engineering concepts such as mechanical assemblies or fluid systems. In this section, I describe how the project files are organized, how the prototype was iteratively developed and tested, how students moved through the experience, and the concrete steps required to utilize and expand this prototype for additional models.

**Project File Organization**

The Visual Studio solution is organized to separate 3D content from scene logic. Figure 4.7 shows the overall project structure in Visual Studio 2022. All anatomy assets are stored under the 'Assets' folder, which contains one GLB file for each system and its corresponding no-label variant (for example, circulatorySystem.glb and circulatorySystemNL.glb). Optimized versions produced with gltfpack (with the .opt.glb suffix) are also stored here and are used where appropriate to reduce processing load on the HoloLens 2. This folder acts as the content library for the application: adding or replacing a system primarily involves modifying the files in this directory.

The core application logic resides in Program.cs and in the 'Scene' folder with three primary classes (AppState.cs, LoadInterface.cs, and SystemsModels.cs). Program.cs contains the StereoKit entry point and the main scene loop that switches between the starting menu and an active body system. AppState.cs maintains shared application state, including the poses for the starting window and model controls window, the current system pose, system scale, label toggle, animation selection, and a small dictionary of chest alignment offsets for each system. LoadInterface.cs defines the user interface windows: a "Starting Window (Main Menu)" with one button per system and a "Model View and Controls" window providing the Back button, scale slider, labels toggle, animation controls (when available), and Reset Models button. Finally, SystemsModels.cs is responsible for loading all labeled and no-label models from the ‘Assets’ folder and, where applicable, starting a default animation clip. This separation keeps content, UI layout, and scene management loosely coupled and makes it easier to update one aspect without rewriting the others.

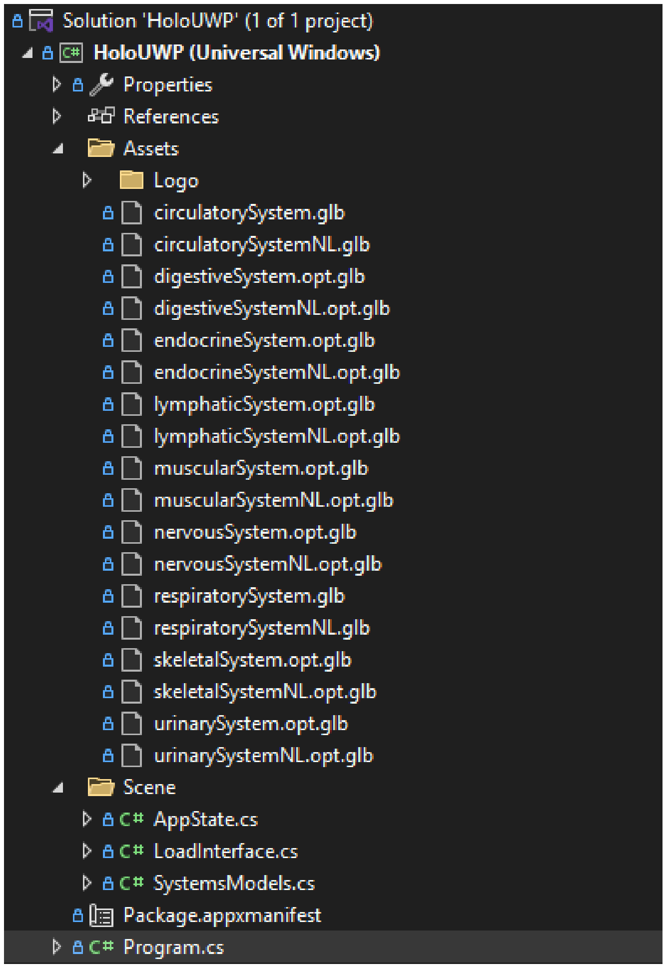

***Figure 4.6:*** *Project structure for the Systems Simulation prototype in Visual Studio 2022*

### Development Process and Testing Workflow

Implementation was tracked using GitHub, with commits reflecting incremental feature additions. Early commits added the core project files and the nine anatomy models, configured for deployment to the HoloLens 2. Subsequent commits focused on interactivity: making the systems grabbable, adding a handle based on the center of each model, and configuring

StereoKit's UI.Handle so that users could reposition the models in space. Later commits introduced the scale slider and Reset Models button, allowing learners to zoom in or out and return to a canonical pose. Additional revisions refined the circulatory system's graphics and positioning using animation playback, and the final set of commits added support for paired labeled and no-label models, so that the same system could be viewed with or without text overlays.

To keep iteration efficient, most of the early development and layout adjustments were performed using StereoKit's built-in simulator on a desktop PC. The simulator allowed me to test menu logic, button presses, scaling behavior, and model placement without compiling and deploying a UWP package to the HoloLens 2 on every change. Once core behaviors were stable, Microsoft's Holographic Remoting was used to stream the application from the PC to the headset, enabling live code updates while viewing the mixed reality scene on the actual device. This combination of the StereoKit simulator, Holographic Remoting, and GitHub version control reduced turnaround time and made it practical to refine the prototype over many small iterations.

**System Flowchart**

Figure 4.7 shows a system flowchart of the interaction between the user and the *Systems Simulation* application. The student first sees the Starting Window (Main Menu), where they can select a body system. When the student taps a system button, the application records the selection and looks up the corresponding labeled and no-label models and chest alignment parameters. The application anchors the selected model relative to the starting window and repositions the Model Controls window so that it appears alongside the model. The student can then reposition and scale the model, toggle labels, and, for systems with animations, play (and loop) the selected animation clips. The student can also press Reset Models to restore the default pose, orientation, and scale. Pressing the Back button stops any active animation, clears the current system selection, and returns the student to the Starting Window, where they can choose another body system. This consistent flow ensures that every system is explored through the same set of interactions (grabbing, scaling, toggling labels, and optionally playing animations), which is important for this study because it reduces variability in interaction patterns and focuses differences in learning outcomes on the content of each system rather than on changes in interface design.

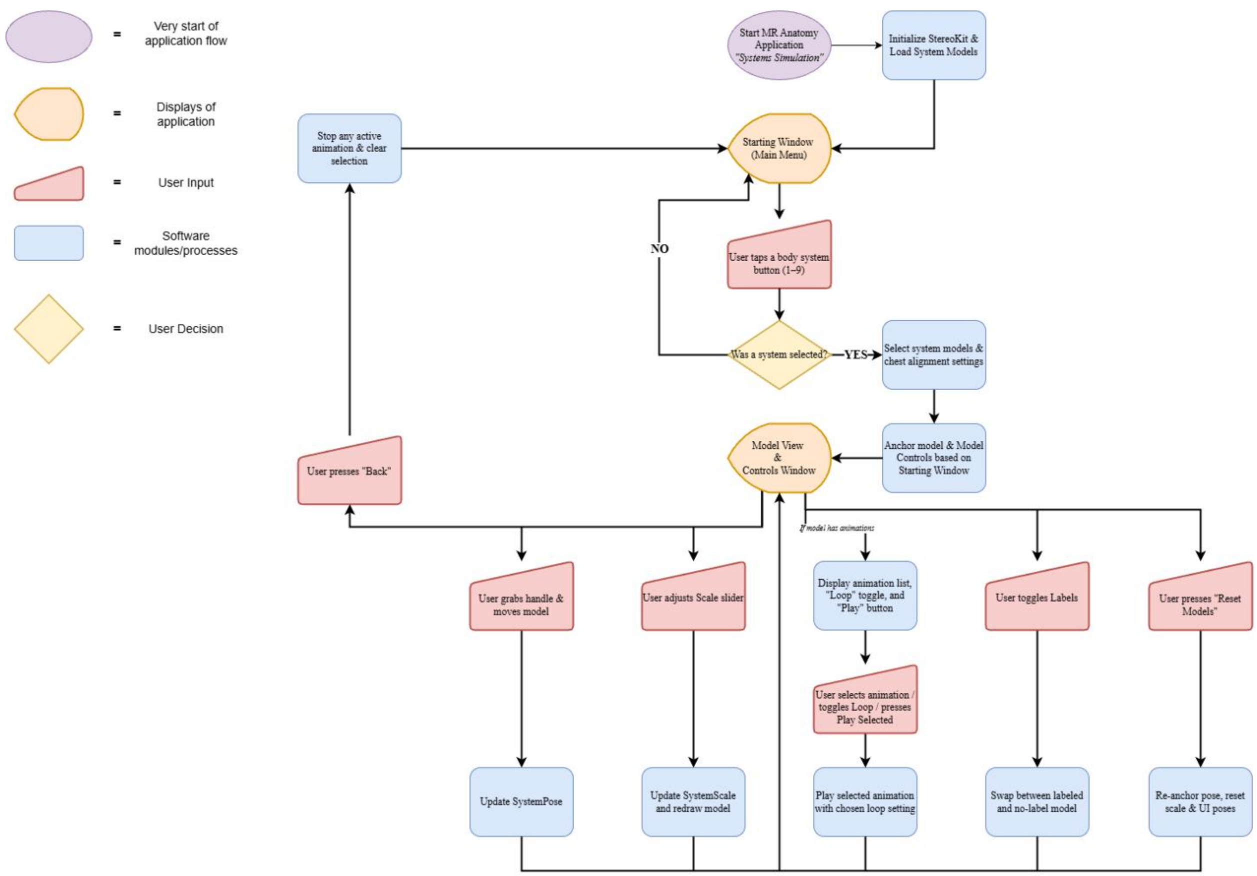


***Figure 4.7:*** *System Flowchart for ‘Systems Simulation’*

**Authoring Workflow for New Models**

Because the application logic is shared across all systems, adding a new model follows a straightforward System extension workflow, summarized below:

1. *Prepare the 3D content:* A new anatomy model is created or adapted in Blender and exported as GLB files, typically with two variants: one that includes baked-in labels and one without labels to support a clean view.

2. *Add assets to the project:* The labeled and no-label GLB files are copied into the 'Assets' folder, following the naming convention used by existing systems (for example, newSystem.glb and newSystemNL.glb). If necessary, the models may be optimized with gltfpack before import (for the optimization workflow, see Appendix X).

3. *Register the models in SystemsModels.cs:* New static fields are added for the labeled and no-label variants, and the LoadAll() method is updated to call Model.FromFile(...) for each file. If the new model includes animation clips, TryPlayFirstAnimation or similar logic can be used to can be used to verify that animations play correctly prior to user selection.

4. *Expose the system in the main menu:* In LoadInterface.DrawStartInterface(), a new button is added for the system. When pressed, this button returns a unique integer identifier, which is passed back to Program.Main.

5. *Map the identifier to the correct models:* The switch statement in Program.cs is extended with a new case that selects either the labeled or no-label model based on the current value of AppState.ShowLabels.

6. *Configure chest alignment:* A new entry is added to the ChestAdj dictionary in AppState so that the handle and model pivot are aligned with the approximate chest region of the new system when it is first anchored.

7. *Test in the simulator and on device:* The new system is exercised in the StereoKit simulator and then via Holographic Remoting on the HoloLens 2 to check that placement, scaling, labels, and animations behave consistently with the existing systems.

By structuring the prototype in this way, *Systems Simulation* functions not only as a one-off anatomy demo, but as an expandable mixed reality framework. Instructors and future developers can add new body systems, or parallel content from other disciplines, by following a predictable sequence of steps without modifying the core interaction logic described in the earlier sections of this chapter.

# Chapter 5 – Study Design and Methodology

In this chapter, I describe how I designed and carried out the preliminary evaluation of the mixed reality anatomy prototype with nursing students. I first outline the study goals and hypotheses, then introduce the participants and lab setting, followed by the instruments used to capture performance, perceptions, and reflections on the MR experience. I then walk through the procedure for the individual sessions and discuss the steps taken to support the validity and ethics of the study. Together, these methodological details connect the prototype and design decisions described in earlier chapters to the learning outcomes and participant perspectives reported in Chapters 6 and 7.

## 5.1. Study Goals and Hypotheses

The evaluation reported in this thesis was designed to examine how a MR anatomy prototype might support nursing students' understanding of body systems, and how they experienced the system as a learning tool. Building on prior work showing that 3D and immersive visualizations can improve spatial reasoning and engagement compared to traditional materials, I structured the study around learning effectiveness and user experience. On the learning side, the MR session was paired with a paper-based short-answer anatomy test and a corresponding MR-based short-answer test that targeted the same underlying systems and concepts. On the experience side, a Likert-scale survey, open-ended reflection questions, and observation notes captured students' perceptions of understanding, spatial relationships, engagement, usability, and future applications of MR in nursing education. Together, this data was intended to provide a mixed-methods picture of how the prototype functioned as an assessment-driven learning activity and an interactive MR interface.

The primary learning hypothesis was that students would be able to answer short-answer anatomy questions at least as accurately in the MR environment as on the paper-based diagrams, even though the MR test required them to locate structures in 3D space rather than on a piece of paper. A related expectation was that students would report stronger perceived understanding of anatomical systems, especially with respect to spatial relationships and the ability to explain how structures and systems interact. On the user-experience side, I expected that students would find the prototype engaging and generally usable, while still revealing specific interaction issues and design opportunities related to gesture controls, labeling, and content depth

## 5.2. Participants and Setting

The study was conducted at St. Mary's University within an undergraduate pathophysiology course that formed of the new nursing program. All data collection took place in the Human-Centered Design Lab, a small Usability Testing space equipped with a table, chairs, and sufficient open floor area for participants to move around while wearing the HoloLens 2 headset. Sessions were scheduled individually and lasted approximately 45 minutes, including consent, testing, the mixed reality experience, and the closing interview.

Thirteen students enrolled in the course volunteered to participate after a brief in-class invitation. Because of scheduling constraints, eight of these volunteers completed the full individual session and constitute the sample reported in this thesis. At the beginning of the session, each participant completed a short paper questionnaire that captured basic demographic information (gender and highest level of education), prior coursework in anatomy, and prior experience with mixed reality or related immersive technologies. The questionnaire is reproduced in Figure 5.1.

***Participant Number:***

***Questionnaire***

1. What is your gender?
    a. Male
    b. Female
    c. Other
    d. Do not wish to answer
2. What is your highest level of education?
    a. Less than high school
    b. High School/GED
    c. Associates
    d. Bachelors
    e. Masters
3. Have you taken anatomy?
    a. Yes
    b. No

3b. If yes, when did you take the course? _________

4. Have you ever used Mixed Reality?
    a. Yes
    b. No

4b. If yes, when was the last time that you've used MR? _____________

4c. If yes, what are the devices on which you've used MR? ___________________

***Figure 5.1:*** *Brief questionnaire used during participant introduction*

## 5.3. Instruments

The evaluation used four primary instruments to capture learning outcomes and user experience: a paper-based short-answer anatomy test, a corresponding MR-based short-answer test, a Likert-scale survey, and a set of semi-structured reflection and interview prompts. Together, these instruments provided aligned quantitative and qualitative evidence about how nursing students interacted with the mixed reality (MR) anatomy prototype.

### Paper-Based Test

The paper-based short-answer test consisted of eight items, one for each of the systems represented in the study (circulatory, digestive, endocrine, lymphatic, muscular, nervous, respiratory, and urinary). For each item, students saw front and back views of a human figure with the relevant system overlaid; the graphics were direct screenshots from the 3D models used in the MR application so that structures and visual style were as comparable as possible across media. Students were asked to identify a specific structure by marking or labeling it on the diagram and then answer a targeted short-answer question about that structure's primary function or a closely related mechanism. Figure 5.2 shows an example item for the digestive system. Two equivalent versions of the test (A and B) were created for a crossover design, where half of the participants completed version A on the paper-based test and version B during the MR-based test, while the other half completed B first and A second. Both versions were reviewed with the course instructor to ensure that the prompts were appropriate for the course and roughly matched in difficulty and content coverage. The complete set of questions and scoring rubric for test versions A and B is provided in Tables A.1 and A.2.

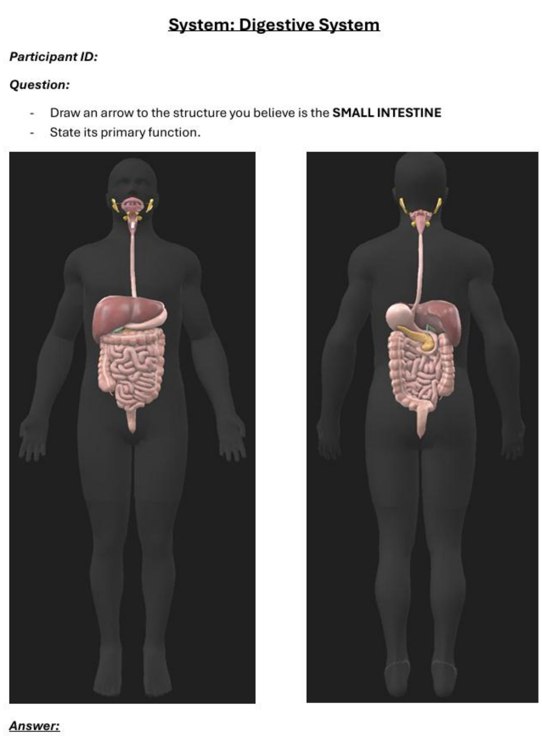


***Figure 5.2:*** *Example paper-based test question for the digestive system (Version A)*

**MR-Based Test**

The MR-based short-answer test paralleled the paper-based questions but was delivered through the MR prototype instead of on paper. After completing the initial paper test and practice tutorial, participants moved through the same eight systems in the headset with labels turned off. For each system, they were asked to point to the target structure in 3D space and provide an oral answer to the corresponding short-answer question (Figures 5.3 and 5.4). The underlying prompts again followed the A/B crossover design so that each participant encountered all concepts across the two media without simply repeating identical items. Responses on the paper- and MR-based tests were scored using the same 1–3 rubric (with half-point increments), where higher scores reflected more complete identification of the target structure and a more accurate, conceptually appropriate explanation. Scores were then summed across the eight items, producing totals from 8 to 24 for each medium (see Table 6.1).

***Figure 5.3:*** *Participant identifying adrenal glands from headset point of view*

*Figure 5.4: Screenshot from volunteer identifying Adrenal Glands from the room camera*

**Likert-Scale Survey**

To capture students' perceptions of learning, usability, and future applications, each participant completed a nine-item Likert-scale survey immediately after the MR session. Items were rated on a five-point scale from 1 ("Completely Disagree") to 5 ("Completely Agree") and were phrased positively so that higher scores indicated more favorable perceptions. Statements targeted understanding of the anatomical systems, memory for spatial relationships, confidence in explaining how systems function, encouragement to think about system interactions, overall engagement, usability of the controls and interface, enjoyment of the immersive environment, and interest in using MR for additional nursing and healthcare topics. Figure 5.5 shows the full survey. The form also provided optional space for brief written comments, although most elaboration occurred verbally; participants sometimes justified their ratings or offered additional comments, and these remarks were incorporated into the qualitative analysis presented in Section 6.4.

***Participant Number:***

***Likert Questions:***

Each statement should be rated on a **5-point scale**:
**1 – Completely Disagree | 2 – Disagree | 3 – Neutral | 4 – Agree | 5 – Completely Agree**

1. The Mixed Reality experience helped me better understand the anatomical system compared to traditional 2D materials.
2. The 3D visualization made it easier to remember the spatial relationships between anatomical structures.
3. Using the Mixed Reality model improved my confidence in explaining how this system functions.
4. The Mixed Reality experience encouraged me to think more critically about how the body's systems interact.
5. I felt fully engaged while using the Mixed Reality platform.
6. The controls and interface of the Mixed Reality system were intuitive and easy to use.
7. The immersive environment made the learning experience more enjoyable.
8. I would prefer to use Mixed Reality for other nursing or healthcare topics in the future.
9. The Mixed Reality platform has potential to improve how nursing students learn complex concepts.

***Figure 5.5:*** *Likert-scale survey*

## Reflection Questions

Finally, participants responded to a brief set of open-ended reflection questions and semi-structured interview prompts that probed how they experienced the MR session and how they envisioned using similar tools in nursing education and practice. The prompts asked about (1) potential benefits of MR for healthcare education, (2) the most engaging or memorable aspects of the experience, (3) comfort interacting with the MR interface, (4) how they would use this technology within healthcare contexts, and (5) features or improvements they would like to see in future versions of the platform. I used these questions as a template for a short follow-up conversation in which participants could elaborate on their responses or introduce additional points. Figure 5.6 shows the reflection and discussion questions as presented to participants.

***Participant Number:***

**Reflection Questions:**

1. Do you believe that Mixed Reality could benefit healthcare education and why?
2. What aspects of the experience were most engaging or memorable for you, and why?
3. How comfortable were you interacting with the Mixed Reality interface, and did that affect your learning experience?
4. How would you utilize this technology within healthcare?
5. Looking back, what would you suggest improving in the Mixed Reality experience to make it more effective for nursing education?

***Figure 5.6:*** *Reflection and discussion questions for semi-structured interview*

### Thematic Coding

Participants' verbal responses to these prompts, along with the rest of the interview dialogue and relevant in-session comment, formed the primary qualitative dataset for the thematic analysis in Section 6.4. I coded these materials manually and iteratively, using a combination of inductive codes that emerged from the data and deductive codes reflecting the study's focus on spatial understanding and 3D relationships, engagement and motivation, perceived learning and confidence, usability and interaction challenges, and future nursing applications and feature improvements.

In addition to these four instruments, each session was recorded using a digital audio recorder (a smartphone), a room camera, and a headset point-of-view capture from the HoloLens 2. These recordings supported accurate scoring of the MR-based short-answer responses and provided contextual detail for interpreting the think-aloud comments, survey remarks, and reflection answers used in the mixed-methods analysis.

## 5.4. Procedure

Each participant completed an individual session lasting approximately 45 minutes in the Human-Centered Design Lab. All eight students followed the same sequence of activities so that scores and qualitative feedback would be comparable across participants. At the beginning of the session, I briefly explained the purpose of the study, obtained informed consent, and asked participants to verbalize their thought processes as they worked through the tasks. Participants then filled out the background questionnaire on gender, education, prior anatomy coursework, and mixed reality experience described in Section 5.2 (Figure 5.1).

After the questionnaire, participants completed the paper-based short-answer anatomy test described in Section 5.3. They were reminded that the activity was not graded and were asked to answer each item as accurately as they could without worrying about it being a grade. No correctness feedback was given at this stage. Once the paper-based test was finished, I provided a short in-headset tutorial covering basic mixed reality interactions such as gaze-based targeting, pinch-and-release selection, grabbing and repositioning content, and using the interface windows. For this familiarization phase, students practiced on a skeletal system model that was not included in any of the scored test items so they could experiment with the controls without affecting their assessment results.

The main MR-based short-answer test followed immediately after the tutorial. With labels turned off, participants stepped through the same eight systems represented on the paper-based test. For each system, I read the corresponding short-answer prompt from the A/B test set while the participant located the target structure in 3D space by pointing to it and giving an oral explanation. Figures 5.3 and 5.4 illustrate this phase from the headset and room-camera perspectives. Once all eight MR questions had been completed, I allowed participants to go back and enabled labels so that they could check how well their responses aligned with the labeled structures.

To conclude the session, participants removed the headset and completed the nine-item Likert-scale survey described earlier (Figure 5.5), after which I asked them a short set of open-ended reflection questions based on the prompts shown in Figure 5.6. I used these prompts to structure a brief semi-structured interview, during which participants answered verbally and expanded on their perceptions about the benefits and challenges of the MR system, their comfort with the interface, and potential applications in nursing education and practice.

## 5.5. Validity and Ethics

Several features of the design were intended to support internal validity. All eight participants completed the same procedure in the same lab environment, with consistent instructions and timing as described in Section 5.4. The crossover use of A/B item sets and unlabeled models during the MR portion (Section 5.3) were chosen to reduce simple recall of specific questions and to keep the focus on underlying concepts rather than recognition of particular screenshots. The think-aloud instructions and tutorial were used to help participants become comfortable with the interface before the scored MR questions began, minimizing early interaction difficulties as a factor that could distort the performance comparison.

Content validity was addressed by aligning all test prompts and MR tasks with the topics and expectations of the pathophysiology course and by working with the course instructor to review item wording and difficulty. The use of the same anatomical source models across the paper-based and MR-based tasks helped ensure that differences in performance reflected the change in medium and interaction (2D diagrams versus 3D spatial exploration) rather than entirely different visualizations. On the qualitative side, the thematic coding process described at the end of Section 5.3 was designed to maintain a close link between participant statements and the five themes reported in Chapter 6, so that claims about spatial understanding, engagement, perceived learning, usability, and future applications remain grounded in participants' actual statements and aligned with the study's focus.

At the same time, several limitations narrow the strength and the generalizability of these findings. The sample was small, consisting of eight volunteers from a single course at my university, and participants self-selected into the study rather than being randomly sampled. The MR headset and immersive content were novel for most students, raising the possibility of a short-term excitement effect on engagement ratings. In addition, I conducted the primary scoring of short-answer responses and the qualitative coding, which introduces the possibility of bias even with a consistent rubric and iterative coding process. These and other threats to validity are revisited in Chapter 7 when interpreting the results and outlining directions for future work.

Ethical considerations were guided by institutional expectations for research with student participants. Volunteers were invited to participate on a voluntary basis during class and were informed that their decision to participate or decline would have no effect on their course grade or standing. At the beginning of each session, participants reviewed an information sheet, had the opportunity to ask questions, and provided written consent before any data were collected. Throughout the session, they were reminded that they could skip any question or stop at any time without penalty. Audio, video, and headset recordings were stored on password-protected devices, and personally identifying information was removed from transcripts by referring to participants only by numeric identifiers (e.g., "Participant 1"). When reporting results in

Chapters 6 and 7, quotes and examples are presented in a way that avoids revealing individual identities or sensitive details.

# Chapter 6 – Results

The results of the mixed-methods evaluation of the mixed reality anatomy prototype are presented in this chapter. I first describe who participated in the study and how they performed on the paper-based and MR-based short-answer tests, followed by participants' Likert-scale ratings of understanding, spatial relationships, engagement, usability, and future applications. I then use qualitative themes and illustrative quotes to show how students actually experienced the MR session moment to moment, how it supported or constrained their learning, and how they imagined using similar tools in nursing education and practice. Together, these results connect the design decisions and methodology outlined in earlier chapters to the broader design implications and case studies developed later in Chapter 7.

## 6.1. Participant Demographics and Session Statistics

All eight nursing participants completed a brief background questionnaire before the study session. The questionnaire asked about gender, highest level of education, prior anatomy coursework, and prior experience with mixed reality or related technologies (Figure 5.1 shows the full questions). Table 6.1 summarizes the responses. The sample included five male and three female students. Six participants reported High School/GED as their highest completed level of education, while two reported having completed an associate's degree.

| Participant | Q1 | Q2 | Q3 | Q3b | Q4 | Q4b | Q4c |
|---|---|---|---|---|---|---|---|
| 1 | Male | Associates | Yes | Spring 2025 | No | | |
| 2 | Male | High School/GED | Yes | Fall 2024 & Spring 2025 | Yes | 2023 | Oculus |
| 3 | Female | High School/GED | Yes | Fall 2024 & Spring 2025 | Yes | Several years ago | VR at arcades |
| 4 | Male | High School/GED | Yes | Fall 2024 & Spring 2025 | Yes | 3+ years ago | Playstation VR |
| 5 | Female | High School/GED | Yes | Fall 2024 & Spring 2025 | Yes | 3+ years ago | Phone headset |
| 6 | Male | High School/GED | Yes | Spring 2025 | Yes | 2024 | Phone, Meta Quest, Oculus |
| 7 | Male | Associates | Yes | Summer 2025 | No | | |
| 8 | Female | High School/GED | Yes | 2023 | No | | |

***Table 6.1:*** *Participant responses based on demographic questionnaire items.*

All participants indicated that they had taken at least one anatomy course (Q3). The timing of this coursework was generally recent: six participants reported anatomy in Fall 2024 and/or Spring 2025, one reported Summer 2025, and one reported 2023. In other words, everyone in the sample had relatively fresh exposure to anatomy content within approximately the last one to two academic years.

Prior experience with mixed reality or closely related VR-style technologies (Q4–Q4c) was more variable. Five participants reported some previous MR/VR experience, while three reported no prior use. Among those with experience, most stated that they had used consumer headsets such as Oculus/Meta Quest, PlayStation VR, phone-based headsets, or VR arcade systems, typically for entertainment rather than formal coursework or industry. The recency of this experience ranged from “several years ago” or “3+ years ago” to 2023–2024, indicating a mix of relatively new and more distant familiarity with immersive interfaces. However, no participant reported prior experience with the Microsoft HoloLens 2 (and most had never seen the device before the study), so there was a relatively comparable baseline when it came to the MR experiment itself.

All eight participants completed the full experiment sequence (questionnaire, paper-based short-answer test, MR tutorial and MR-based short-answer test, Likert survey, and reflection questions) so the quantitative and qualitative results reported in Sections 6.2–6.4 are based on the same set of individuals.

## 6.2. Short-Answer Test Results (Paper vs MR)

Table 6.2-6.4 summarize the accuracy scores on the paper-based and MR-based short-answer anatomy tests for the eight nursing participants (see Tables A.1 and A.2 for the complete set of test questions and scoring guidelines). Tables 6.2 and 6.3 report, for each question, the 1–3 accuracy scores earned by each participant on the paper and MR tests, respectively, along with per-question and per-participant totals and average scores. Table 6.4 aggregates these data, showing for each student their total and average score on the paper and MR tests, the resulting change across formats, and the overall total and average changes across participants and questions.

Across all eight participants, total accuracy scores were slightly higher on the MR test than on the paper test. The mean paper-test total was 19.25 out of a possible 24 points, increasing to 20.19 on the MR-test, a gain of 0.94 points, or roughly four percentage points on the 24-point scale. While this difference is not dramatic, it indicates that most students were able to answer slightly more accurately when working in the MR environment, despite the limited sample size and the added variability of alternating test versions.

Question-level patterns suggest that some systems benefited more than others from the MR experience. Average scores increased on the circulatory (Q1; +0.13 points), endocrine (Q3; +0.13), lymphatic (Q4; +0.50), nervous (Q6; +0.50), and respiratory (Q7; +0.19) systems. The largest mean gains were seen on the lymphatic and nervous system questions, which required students to recall the primary function of organs such as the thymus and to classify and describe the role of structures like the spinal cord or median nerve. In contrast, performance on the muscular system (Q5) remained essentially unchanged across formats (1.88 on both tests), and there were small decreases on the digestive (Q2; −0.31) and urinary (Q8; −0.19) systems. Given the crossover A/B format and the different prompts attached to each version (e.g., small intestine vs. liver; kidney vs. ureter), these small declines likely reflect a combination of item difficulty and version differences rather than a straightforward loss of understanding.

As shown in Table 6.4, six of the eight students scored higher on the MR test than on the paper test, with gains ranging from +1 to +4 points on the 24-point scale. Two participants scored lower on the MR-test (−1 and −5.5 points, respectively), producing a pattern of participant question average changes that ranged from −0.69 to +0.50 points per item. This variability is not surprising given the small sample and the open-ended, short-answer format; small shifts in partial credit (e.g., correctly identifying a structure but only partially explaining its function) can meaningfully influence totals for individual students.

The scoring notes also suggest that some of the benefits of the MR format may be better captured by the quality and strategy of students' responses rather than by total scores alone. On the MR test, several participants provided more detailed explanations or incorporated additional structures into their reasoning (e.g., Participant 1 adding more detail to their circulatory answer; Participant 5 describing airflow and alveolar function after previously missing the question on the initial paper test). Others began to use spatial strategies such as walking around the model or using neighboring organs as landmarks when identifying structures. These patterns foreshadow the spatial and conceptual shifts described in the Likert ratings (Section 6.3) and reflection themes (Section 6.4), but at the level of accuracy they appear as modest overall gains with substantial individual variation.

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using neighboring organs as landmarks when identifying structures. These patterns foreshadow the spatial and conceptual shifts described in the Likert ratings (Section 6.3) and reflection themes (Section 6.4), but at the level of accuracy they appear as modest overall gains with substantial individual variation.

It is also important to note that a small number of items were consistently challenging and likely pulled the overall averages downward. In particular, several questions asked about pathophysiology details or hormonal feedback relationships in which many participants either missed outright or earned only partial credit, even when their responses showed reasonable intuition or use of spatial reasoning strategies.

## 6.3. Likert Survey Results

As described in Chapter 5, after completing the mixed reality (MR) session each of the eight nursing participants filled out a nine-item, 5-point Likert survey, with higher scores indicating stronger agreement with positively worded statements about understanding, spatial relationships, engagement, usability, and future applications of MR. The full wording of the nine statements is shown in Figure 5.5. Table 6.5 displays each participant's ratings on the nine Likert items, along with the mean score for each statement and the overall average across all items and participants. Throughout all statements, the grand mean rating was 4.72 out of 5, with item averages ranging from 4.25 to 5.00 and no individual rating below 3. This pattern indicates a generally strong agreement that the MR experience was helpful and acceptable across multiple themes.

| Participant | Group | Version | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A->B | A | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 22 |
| 2 | A->B | A | 1 | 3 | 2 | 2 | 2 | 3 | 2.5 | 2 | 17.5 |
| 3 | A->B | A | 3 | 3 | 3 | 2 | 2 | 3 | 2.5 | 2 | 20.5 |
| 4 | A->B | A | 3 | 3 | 4 | 2 | 2 | 3 | 3 | 3 | 23 |
| 5 | B->A | B | 3 | 3 | 1 | 1 | 2 | 1 | 2 | 3 | 16 |
| 6 | B->A | B | 2 | 3 | 2.5 | 1 | 1 | 1 | 2.5 | 3 | 16 |
| 7 | B->A | B | 3 | 3 | 2 | 3 | 2 | 1 | 3 | 3 | 20 |
| 8 | B->A | B | 3 | 3 | 2 | 2.5 | 2 | 3 | 2.5 | 1 | 19 |
| | | **Question Totals:** | 21 | 24 | 19.5 | 15.5 | 15 | 18 | 21 | 20 | **154** |
| | | **Average Score:** | 2.625 | 3 | 2.4375 | 1.9375 | 1.875 | 2.25 | 2.625 | 2.5 | 19.25 |

***Table 6.2:*** *Paper-based short-answer anatomy test scores by participant and question (1–3 accuracy scale), with per-question and per-participant totals and average scores.*

| Participant | Group | Version | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A->B | B | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 23 |
| 2 | A->B | B | 3 | 2.5 | 2.5 | 2 | 2 | 3 | 3 | 1 | 19 |
| 3 | A->B | B | 3 | 2 | 2.5 | 2 | 1 | 1 | 2.5 | 1 | 15 |
| 4 | A->B | B | 3 | 3 | 2.5 | 2.5 | 2 | 3 | 3 | 3 | 22 |
| 5 | B->A | A | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 2 | 20 |
| 6 | B->A | A | 1.5 | 2 | 3 | 2 | 1 | 3 | 2 | 3 | 17.5 |
| 7 | B->A | A | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 2.5 | 22.5 |
| 8 | B->A | A | 2.5 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 22.5 |
| | | **Question Totals:** | 22 | 21.5 | 20.5 | 19.5 | 15 | 22 | 22.5 | 18.5 | **161.5** |
| | | **Average Score:** | 2.75 | 2.6875 | 2.5625 | 2.4375 | 1.875 | 2.75 | 2.8125 | 2.3125 | 20.1875 |

***Table 6.3:*** *Mixed reality short-answer anatomy test scores by participant and question (1–3 accuracy scale), with per-question and per-participant totals and average scores.*

| Participant | Group | Total Change | Paper Average | MR Average | Average Change |
|---|---|---|---|---|---|
| 1 | A->B | 1 | 2.75 | 2.875 | 0.125 |
| 2 | A->B | 1.5 | 2.1875 | 2.375 | 0.1875 |
| 3 | A->B | -5.5 | 2.5625 | 1.875 | -0.6875 |
| 4 | A->B | -1 | 2.875 | 2.75 | -0.125 |
| 5 | B->A | 4 | 2 | 2.5 | 0.5 |
| 6 | B->A | 1.5 | 2 | 2.1875 | 0.1875 |
| 7 | B->A | 2.5 | 2.5 | 2.8125 | 0.3125 |
| 8 | B->A | 3.5 | 2.375 | 2.8125 | 0.4375 |
| | **Question Totals:** | **7.5** | | | |
| | **Average Score:** | 0.9375 | | | |

***Table 6.4:*** *Per-participant total and average short-answer test scores on the paper and MR tests, and their changes across formats, including overall total and average changes across participants and questions.*

| Participant | Statement 1 | Statement 2 | Statement 3 | Statement 4 | Statement 5 | Statement 6 | Statement 7 | Statement 8 | Statement 9 | Average Score |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 5 | 4 | 5 | 5 | 5 | 5 | 4 | 5 | 4.67 |
| 2 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 4.89 |
| 3 | 5 | 4 | 3 | 4 | 5 | 5 | 5 | 4 | 4 | 4.33 |
| 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5.00 |
| 5 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 4.89 |
| 6 | 5 | 4 | 4 | 5 | 4 | 3 | 5 | 5 | 5 | 4.44 |
| 7 | 4 | 5 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 4.78 |
| 8 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 4 | 5 | 4.78 |
| Average Score | 4.75 | 4.75 | 4.25 | 4.875 | 4.75 | 4.625 | 5 | 4.625 | 4.875 | 4.72 |

***Table 6.5:*** *Participant ratings to the Likert-scale survey statements, with a mean rating for each statement and overall average rating across all items and participants.*

Statements 1–4 targeted conceptual and cognitive aspects of learning: overall understanding of the anatomical system (Statement 1), memory for spatial relationships between structures (Statement 2), confidence in explaining how the system functions (Statement 3), and encouragement to think about how body systems interact (Statement 4). Mean ratings were 4.75 for Statement 1 (range 4–5), 4.75 for Statement 2 (range 4–5), 4.25 for Statement 3 (range 3–5), and 4.88 for Statement 4 (range 4–5). Participants therefore strongly agreed that the MR experience helped them better understand the anatomical system compared to traditional 2D materials and that 3D visualization made it easier to remember spatial relationships between anatomical structures while being encouraged to think more critically about how body systems interact. Confidence in explaining how the system functions (Statement 3) was slightly lower than the other items in this survey, but still above 4 on average. The single lowest rating in this cluster of statements was a score of 3 on Statement 3, indicating that one participant was more cautious about claiming full explanatory confidence, even though they still agreed overall with the positive learning impact.

Engagement-focused items received some of the strongest endorsement. Statement 5, which dealt with overall engagement while using the MR platform, had a mean of 4.75 (range 4–5). Statement 7, on the enjoyment of the immersive environment, produced the highest possible result in which every participant rated this item as 5, yielding a mean of 5.00. Together, these items show that the MR prototype was experienced as highly engaging and enjoyable, a pattern echoed in additional comments describing the session as “really engaging” and “a lot more fun than paper and slides.”

Perceptions of usability and future application were also positive. Statement 6, which asked about the intuitiveness and ease of use of the controls and interface, had a mean rating of 4.63 (range 3–5). The lower ratings were linked in comments to occasional difficulties with pinch gestures and hand tracking, particularly with the left hand, rather than confusion about the interface itself. Other participants explicitly attributed occasional pinching difficulties to “user error” and reported that the interface felt intuitive once they had practiced the gestures, suggesting that usability concerns were present but not dominant.

The final two items focused on future use and broader educational potential. Participants agreed that they would prefer to use MR for other nursing or healthcare topics (Statement 8; M = 4.63, ratings 4–5) and that the MR platform has potential to improve how nursing students learn complex concepts (Statement 9; M = 4.88, ratings 4–5). Several participants mentioned applications such as visualizing disease processes or using MR as a supplement to traditional lectures which align with the “Future nursing applications/Feature improvements” theme developed later in Section 6.4.

## 6.4. Reflection Responses and Illustrative Quotes

While the paper- and MR-based short-answer tests and the Likert-scale ratings provide a quantitative picture of how participants responded to the mixed reality (MR) experience, they do not fully capture how students experienced the system moment to moment. To address this, I analyzed open-ended reflection questions, in-session comments during the tutorial and prototype exploration, and additional remarks on the Likert survey using the qualitative approach described in Section 5.5. The full wording of the nine Likert-scale statements is shown in Figure 5.5, and the complete wording of the reflection questions is provided in Figure 5.6. This analysis was aimed at understanding how nursing students made sense of the MR environment as a learning tool, where it supported or constrained their learning, and how they imagined using similar tools in their future practice.

Using this approach, I identified five themes that summarize participants' experiences:

1. *Spatial understanding and 3D Relationships:* how MR supported seeing structures in depth, locating organs relative to one another, and using movement around the model to reason about the body in space.

2. *Engagement and Motivation:* the extent to which the immersive, interactive format captured attention, made learning feel enjoyable, and increased motivation to spend more time with the material.

3. *Perceived Learning and Confidence:* participants' self-reported sense that they learned or reinforced content, felt more confident explaining systems, and believed MR could help with long-term understanding.

4. *Usability and Interaction:* how students experienced the interface, gesture controls, and overall interaction with the system, including practical issues related to hand tracking, field-of-view, and gesture recognition that occasionally disrupted the experience or required adjustment.

5. *Future Nursing Applications/Feature Improvements:* ways participants envisioned MR being integrated into nursing education and clinical contexts, along with suggestions for additional features and scenarios.

These themes are not completely isolated from one another. For example, comments about spatial understanding were often intertwined with high engagement ("I liked being able to walk around and see the back side of the model and the space between different systems and organs") or tied to perceived learning ("With the headset, you can see through and see those deeper structures, and that helps you think through how they work."). Similarly, many suggestions for future applications emerged directly from moments of strong engagement or from frustrations with specific interaction issues. Rather than treating each theme as a separate category, the analysis below highlights how they overlap while still organizing the presentation around the primary focus of each theme.

In the subsections that follow, I describe each theme in more detail, using illustrative quotes and relevant observation notes to characterize how students experienced the mixed reality anatomy prototype.

### 6.4.1. Theme 1- Spatial Understanding and 3D Relationships

This theme captures how participants used the 3D mixed reality environment to understand where structures are located and how systems relate in space. Across the Likert survey comments, reflection responses, and observations during the MR-based test, students repeatedly described benefits that depended on depth, multiple viewpoints, and the ability to move around the model. Rather than treating the MR session as a fixed picture, participants used it to orient themselves, compare neighboring structures, and reason about flows and pathways in three dimensions.

Several participants contrasted the MR models with traditional 2D diagrams, emphasizing that the 3D context made it easier to know “where you are” in the body. In a Likert survey extra comment to Statement 1, which asked whether the Mixed Reality experience helped them better understand the anatomical system compared to traditional 2D materials, Participant 3 explained, “I really liked it because looking at pictures is harder to understand. Sometimes I feel like pictures in anatomy need a compass—you have no idea where you are, or if it just shows you a random bone you have no idea where it is. Seeing it on the 3D model was definitely easier for me to understand.” Participant 6, responding to Statement 2 about remembering spatial relationships between anatomical structures, described how depth and changes in viewpoint directly supported spatial reasoning: “It did make it a little easier, the spatial stuff. The best way I did it was I had to spin around; otherwise I could kind of tell the spatial difference, but when I turned to the side I could definitely see it. If I was just looking face forward, I could see it, but not 100%.” In response to reflection Question 1 about potential benefits for healthcare education, Participant 5 highlighted the ability to inspect deeper regions: “You can zoom in and really look at structures. It’s more helpful than just imagining them, because when you look at a person you can’t see things like the thalamus. With the headset, you can see through and see those deeper structures, and that helps you think through how they work.” Together, these accounts show that participants were actively using rotation, zoom, and side views to resolve ambiguities that 2D images often left unclear.

Movement around the model and the sense that the holograms were anchored in the room were also central to how students experienced spatial relationships. In response to reflection

Question 2 about the most engaging or memorable aspects of the experience, Participant 2 described how switching systems and seeing them in place made structures stand out: “Being able to choose which system I was looking at, and then seeing it pop up in front of me. I liked being able to walk around and see the back side of the model and the space between different systems and organs. All of that really popped out to me.” In another response to the same question, Participant 6 emphasized the experience of walking around the model itself: “I really liked being able to move around and actually zoom in on something if I wanted to. The little animations helped too. You could see how the system was working—like seeing the blood pumping to a certain area or the diaphragm going down to let the lungs expand.” Participant 8, when asked the same, linked their enjoyment directly to being able to move relative to the hologram: “I think moving the screen around and moving the body around was really cool. Then I could go around it and see the back of it. That was super cool.” These comments highlight that students were not only manipulating the model with their hands but also repositioning themselves in the physical space to see structures from behind and from multiple angles.

Participants also described using surrounding structures and bodily movement as spatial anchors to locate specific targets and reason about pathways. In response to Statement 4 about thinking critically about how the body’s systems interact, Participant 3 noted that the MR session “helped with spatial relationships and made it easier to see directions of flow, like when we were looking at the circulatory system and I could actually point and show the way it goes, instead of just drawing arrows on paper. Like it’s just easier for me to understand. Looking at how close different systems are also helped me think about their interactions.” Participant 6 reflected on deliberately using other organs as landmarks: “When I was trying to figure out where stuff was, I was thinking, ‘From what I remember, how do I find where this is at?’ I used other organs and other structures to help me find it, and that really encouraged me more—me being more of a kinesthetic learner." The MR-based testing notes showed similar strategies. Several participants mentioned kidneys to help identify nearby structures, walked around the model to confirm muscle locations, and used their hands to demonstrate blood flow, respiratory airflow, digestive paths, and urinary flow in mid-air while explaining their answers on the MR-based test. These behaviors suggest that students were actively reconstructing the 3D layout of systems by combining visual landmarks with embodied gestures.

### 6.4.2. Theme 2- Engagement and Motivation

This theme captures the extent to which the immersive, interactive mixed reality (MR) format captured students' attention, made learning feel enjoyable, and increased their motivation to spend time with the content. Across reflection responses, Likert survey comments, and in-session remarks, participants frequently described the headset experience as "fun," "cool," and more engaging than slides or paper-based materials. Rather than treating the MR session as just another assignment, students described it as an interesting and highly involving activity that made it easier to stay focused on the material.

Several students contrasted the MR session with their usual experiences of studying from slides or textbooks, emphasizing that the prototype made studying feel less boring and easier to stay engaged. In a response to reflection Question 1 about potential benefits for healthcare education, Participant 3 explained, "It makes studying more engaging and less boring. My issue with studying is that I get really zoned out—I get distracted by nothing. It's harder to zone out when all you can see is the skeleton, right in front of you, and it's 3D. I think that would help." When later asked Question 2 on what aspects of the experience were most engaging or memorable, the same student added, “I liked that it was kind of fun and not just boring; that made it engaging. I liked that it was something new and it made me feel very cool. Feeling cool helps with studying—sometimes I feel like a loser nerd, and that demotivates me.” In response to the same question, Participant 1 similarly described how the presentation of content itself demanded attention: “Memorable is how the headset looks—I think it looks very cool. It was engaging because the content is right in your face with what you need to learn. You can’t really escape it, so I think it’s very engaging.” Together, these accounts suggest that participants experienced MR as a more compelling and self-motivating way to study than their usual text- or slide-based methods.

Engagement was also tied to the physicality of the experience, stemming from the fact that students were standing, moving, and interacting with a hologram anchored in the same room. In a Likert survey extra comment to Statement 7 on whether the immersive environment made the learning experience more enjoyable, Participant 6 wrote, “I think because I was standing up, I was actually really engaging with it. When I’m sitting in class, I’m engaging and answering questions, but when I was using the mixed reality it made me able to visualize it more and made it more fun, because I wasn’t just sitting down at a desk with my friends alongside me.” Participant 7, rating the same item, summarized the contrast: “That was a lot more fun than paper and slides.” Reflection responses point to similar patterns. In response to reflection Question 2 about the most engaging or memorable aspects of the experience, Participant 7 highlighted how the holograms filled the physical room without causing discomfort: “It was the room environment. Whenever I think about virtual reality, I think I’m going to get a little sick, but I didn’t feel anything. It was super interesting having the same room you’re physically in, but still being able to see a structure of something. The movement of the heart and diaphragm looked like what we studied before, so it still looked really realistic. I liked it." Participant 5 noted, "I thought it was really cool that the model is set up to the whole room. I'm not worried I'm going to walk into a wall. I also liked how you showed the heart pumping and the lungs moving—the animations were really cool." These comments indicate that enjoyment came not only from the content but from moving around with it in a familiar space.

Beyond making a single session feel enjoyable, some participants explicitly linked mixed reality to their motivation to spend more time studying. After completing the MR session, Participant 3 remarked, "Yeah, I feel like I could sit for hours and play with it, and then I'd probably get smarter in the process." In a Likert survey comment to Statement 5, which asked whether they felt fully engaged while using the Mixed Reality platform, Participant 4 connected their enthusiasm to a desire for broader adoption: "I'm a big fan of technology and moving forward, so hopefully one day this can be an everyday thing." Participant 6, responding to Statement 9 about the platform's potential to improve how nursing students learn complex concepts, framed MR as better aligned with their generation's attention patterns: "I think that a lot of the time, especially with my generation, with the amount of technology we deal with, we have a smaller attention span, and I feel like it's harder for us to learn things with just pen and paper. I think, for instance, if you interact with stuff, it's a lot easier to learn because I know that a lot of my classmates learn a lot better when we are doing experiments in comparison to just writing notes." These statements suggest that students saw MR not only as enjoyable in the moment but as a style of learning that fits how they prefer to study more generally.

### 6.4.3. Theme 3- Perceived Learning and Confidence

This theme captures how students felt the mixed reality session affected their learning, including their sense of understanding, retention, and confidence in explaining anatomical systems. Across reflection responses, Likert survey comments, and MR-based testing notes, participants repeatedly framed the headset as something that would have helped them in past courses, fit their preferred learning styles, and could enhance performance among future nursing students.

Several students linked the mixed reality experience directly to doing better in anatomy and previous coursework. In a reflection response to Question 1 about potential benefits for healthcare education, Participant 3 remarked, “I do think that mixed reality could benefit healthcare education. If I had had it during anatomy and physiology last year, I think I would have done better in the class. It works better with my learning style, and a lot of people learn the same way I do.” Participant 2, reflecting on the same question, emphasized how mixed reality could provide more meaningful exposure than traditional materials: “I definitely think it could help benefit healthcare education. Most of what we do in the nursing program is mainly to pass a test at the end of the day. With this, we could get ‘somewhat’ hands-on experience learning about disorders or patients that come in. If we can’t use the mannequins, we could use this instead.” Participant 4 similarly highlighted the fit with visual learning: “Instead of just reading over slideshows and notes, you can actually see. For people that learn better visually, stuff like that—I mean, I think anyone, whether they’re a visual learner or not, would just have an easier time with this than paper.” Together, these reflections suggest that students saw mixed reality not simply as novel, but as a more effective format for understanding and retaining complex content.

Participants also described feeling more confident in their understanding when they could see and manipulate structures in 3D. When asked explicitly whether 3D visualization helped them feel more confident in their understanding, Participant 1 responded, “Yes. 3D visualization does help me feel more confident in my understanding.” Participant 3, responding to Question 5 on how mixed reality could support future learners, suggested that the platform would be useful as an ongoing study tool: “I think it would be really beneficial. Since this one was specifically anatomy, I think it would be helpful as a study tool for anatomy students.” In a Likert survey extra comment to Statement 1 on whether the Mixed Reality experience helped them better understand the anatomical system compared to traditional 2D materials, Participant 4 explained that being able to “just look around” the median nerve in the holographic model helped them make sense of it, rather than relying solely on memory of diagrams. These accounts show that participants associated the 3D views with a stronger grasp of the material.

For some students, perceived learning gains were most evident when they described how the session helped them recall previously learned topics. In a Likert survey extra comment to Statement 3 about confidence in explaining how this system functions, Participant 4 wrote, “It’s been a while since I’ve had to remember what they were, but it definitely helped seeing a physical structure in front of you.” Participant 7, commenting on Statement 1 on whether the Mixed Reality experience helped them better understand the anatomical system compared to traditional 2D materials, reported that the model “helped me with the median nerve even though I didn’t get it correct, but it helped me remember it wasn’t part of the CNS because I got to physically look at it and kind of get into it. It made me remember something.” These comments suggest that students were using the mixed reality model to reinforce partially formed mental models, even in cases where test answers were not fully correct.

Observations from the MR-based test further support this theme of perceived learning and emerging confidence. The MR test notes document several instances where participants elaborated more in their MR answers than on the equivalent paper questions or used the hologram to refine their thinking. For example, Participant 1 provided more detail in their MR response to the first circulatory question than on the paper test and identified multiple relevant secretions when answering the digestive system question, indicating a richer explanation than initially recorded. In other cases, students' self-corrections during the MR test, such as realizing that a previously chosen ureter label was actually the urethra after demonstrating the urinary pathway. These moments indicate that they were using the model to check and clarify their explanations rather than simply guessing. These behaviors align with participants' verbal reports that the platform helped them "think through" how systems work and supported their confidence in what they were saying.

### 6.4.4. Theme 4- Usability and Interaction

This theme focuses on how students experienced the interface, gesture controls, and overall interaction with the mixed reality (MR) system, including moments where the controls felt intuitive and instances where hand tracking or field-of-view issues disrupted the experience. Across reflection responses, Likert survey comments, and MR-based testing notes, participants generally reported that the core interactions were straightforward once they had a bit of practice, but they also described a learning curve with mid-air pinch gestures, occasional hand-tracking problems (especially with the left hand), and difficulties with the headset's tracking and view framing.

Several students described becoming comfortable with the interface once they had time to practice the gestures. In response to reflection Question 3 about how comfortable they felt interacting with the mixed reality interface, Participant 1 explained, “I was comfortable. I have previous VR experience (though not mixed reality), so that helped. I felt confident, and the interface was very intuitive.” Participant 5, reflecting on the same question, described an initial learning curve followed by greater ease: “At first it took me a second to learn, but once I figured it out I felt a lot more comfortable getting closer and pressing things. I don’t think it hurt my learning. You always have to learn how to use something before you’re comfortable with it; you can’t expect to be an expert.”

At the same time, a number of participants highlighted specific interaction issues that occasionally interrupted the flow of the session. Several students differentiated between the unfamiliarity of AR gestures and problems with the system itself, describing most of the awkwardness as something they would adapt to over time.

In a Likert survey extra comment to Statement 6 about the usability of the controls and interface, Participant 3 remarked, “I agree. With practice, pointing your finger at air will feel more normal. That was the hardest part for me, but I don’t think that was the system—that’s just AR.” Participant 4, reflecting on the same statement, similarly attributed difficulties to their own adjustment to the pinch gesture rather than the design of the interface: “Even though I was pinching a lot, that’s more like user error in my opinion.” In contrast, Participant 6 used the same statement to justify a more cautious usability rating: “When I was trying to interact with it, a lot of the time I would be pinching it, then move it down a little bit, and it would stop midway. I was trying to drag it to a certain area and it would register that I was pinching, but then I’d lose hold of it. When I was trying to click with my left hand, it was a lot less responsive than my right hand for some reason."

Participant 7, in an extra comment to Statement 5 about their engagement rating for the session, noted that they gave a slightly lower score "because the left-hand thing kept it kind of bending and it threw me off a little bit." In response to reflection Question 3 about their comfort with the interface, the same participant explained, "I was pretty comfortable with it. The only thing was the slight glitching where the image would tilt even when my hands were open and I wasn't pinching anything. The left-hand issue kept doing that every time I pinched and then opened my hands, and sometimes I'd look down so the image would cut off—almost like looking at a TV screen. That might have been why. But other than that, that was the only issue." Taken together, these comments suggest that while the basic interaction model was understandable, small inconsistencies in pinch recognition, hand responsiveness, and field-of-view limits could momentarily break immersion and require users to pause and reorient.

MR-based testing notes further illustrate how students adapted to the interface over time and how interaction issues showed up during task performance. Several participants were observed saying they had "gotten more used to" grabbing and rotating the models by the end of the MR-based test and discovered that stepping closer, changing their angle, or slightly adjusting their hand position made pinch-and-drag actions more reliable. In a few cases, participants briefly lost their grip on the model or had it move in an unintended direction, then corrected by trying the gesture again or repositioning themselves relative to the hologram. These observations support the idea that participants were actively experimenting with the interaction mechanics, identifying what worked and where the system could be made smoother.

### 6.4.5. Theme 5- Future Nursing Applications/Feature Improvements

This theme focuses on how participants imagined using mixed reality (MR) beyond a single anatomy lesson, as well as the specific features they felt would make the platform more effective for nursing education. Across reflection responses, additional comments on future-facing Likert items, and observation notes, students envisioned MR as a tool for pre-clinical “practice” encounters, surgical planning, and patient education. At the same time, they proposed concrete feature enhancements. such as additional animations, disease visualizations, and embedded explanations, which would better align the prototype with real nursing tasks and complex pathophysiology.

Several participants described ways they would integrate the platform into pre-clinical training and simulation. In response to reflection Question 4 about how they would utilize this technology within healthcare, Participant 2 proposed using MR to offer clinical exposure before students reach the workforce: “I would use it for clinical immersions before we’re able to actually go into real clinical sites. For example, if some students couldn’t go to a site, this could be very beneficial—especially combined with the mannequins we already have—so not just a few people get the experience, but everyone can.” Participant 8 imagined a patient-based simulator that would let students practice diagnostic reasoning in a safe environment: “I would make a clinical simulator of a patient in a room. You are trying to figure out what is wrong. Maybe the thing that I saw there could be laying in a bed and you have to figure out which part of it is damaged. Something in a clinical setting. That is what I would do.” They emphasized that this would allow learners to make mistakes and restart without harming real patients: “You are able to make mistakes. You can make mistakes and start over and try again. I feel like that is really important for nursing students to learn. We can make mistakes, but you have to learn from them. I think having experience doing something like this would help people not feel so nervous when we have actual human people to do stuff on.” Together, these accounts frame MR as a way to expand access to hands-on practice and reduce anxiety before clinical placements.

Other students, responding to the same reflection Question 4, looked ahead to more advanced uses in surgery and patient-facing encounters. Participant 1 suggested that MR could function as an intraoperative guide and coordination tool: “It could be used in surgery to find where cuts and incisions should be made, or as an overlay for tasks and objectives for a nursing team. Doctors already wear face shields, so if the technology could be implemented into something like a face shield, it would be perfect, honestly.” Participant 5 envisioned MR supporting surgical planning and virtual assessments: “I think it would be really cool for upcoming surgeons. They could use VR or MR to look at where they’d be doing incisions or stitches. It could also be used in a healthcare scenario where you approach a patient and do an assessment on them in VR—having a virtual person there who talks to you. I know there are some computer-based tools like that, but using a headset would be really cool.” Participant 4 described broader classroom and disease-focused uses, explaining, “Seeing diseases and stuff like that. It would be cool in any class if you could just sit down and interact with all that stuff, kind of like Tony Stark would. That would make things a lot easier.” These reflections suggest that students were already extrapolating from a single anatomy prototype to a range of future nursing applications, from operating rooms and surgical assistance to interactive disease-focused teaching.

Participants also highlighted the potential of MR for patient education and explaining complex conditions visually. Building on the idea of using MR beyond student learning, Participant 4 suggested that the platform could support clearer communication with patients: “I also think it would be helpful if there could be recordings that show different body processes." When asked to elaborate, that same participant stated, "because patients don't have the education, and I feel like doctors and nurses sometimes forget that." Participant 3, in a Likert survey extra comment attached to Statement 8 on their preference to use MR for other nursing or healthcare topics, noted that they were optimistic about utilizing MR as they progressed into clinicals: "I'll be doing clinicals, and I think I'll get more used to seeing the variation between patients, but I still think MR would be really helpful." These comments indicate that students were not only thinking about MR as a study aid for themselves, but also as a way to communicate pathologies and procedures to patients and to prepare for the variability they will encounter in practice.

In response to reflection Question 5, students provided detailed suggestions for features that would make the platform more effective for nursing education. Participant 3 focused on adding additional animations and disease-state visualizations: "The main thing I would improve is making more animations. As more of an addition, if there was a way to make the lungs semi-transparent so you could see inside them, and then add conditions like COPD—it was one of the questions you asked me. If you could make an animation where you zoom in on the lungs, they're kind of transparent, and you can see what is actually happening with COPD, I think that would help with learning a lot." Participant 4 emphasized multi-layered anatomy and more dynamic system behavior: "I'd suggest making more animations—like seeing the blood actually pump through the heart and back to the heart, or urine flow, etc. Also being able to zoom in so you can see different layers, like for the muscular system—going under the first layer for your abs—and seeing inside the heart by zooming in. If you could click or pinch the heart and it pulled up a bigger model you can look into, that would be pretty cool—seeing the two ventricles and the blood going through the valves while it's animated." Participant 8, also responding to Question 5, proposed using the interface to layer in condition-specific changes: "Maybe it would be cool if you could add different diseases to the parts on the body. Maybe you can click whatever condition you would be seeing, like this person has cirrhosis, and then it would show in the digestive system a black, kind of icky-looking liver." These suggestions demonstrate an interest in moving beyond static structures towards interactive, condition-based animations that reflect the kinds of content nursing students struggle with in lectures.

Students also recommended improvements to the information design of the prototype so that it could better support reasoning about function and pathology. In a Likert survey extra comment to Statement 3 about confidence in explaining how this system functions, Participant 5 suggested linking labels to explanations: "It would be cool to have explanations with the labels." The same participant elaborated in their response to reflection Question 5, explaining that when "you turn on labels and click an organ—like the pancreas—it would be helpful if an additional bar came down with information. For example, you could click the pancreas and see what it does and what kinds of patient problems might be related to it. Or click the lungs and see that if something is wrong, conditions like COPD might happen. It would be good if each organ label linked to its function and some common pathologies." Together, these comments reinforce the idea that future versions of the platform should integrate explanatory text, functional descriptions, and visual representations of disease processes directly into the 3D models.

# Chapter 7 – Discussion

In this chapter, I move from reporting what happened in the study to explaining what those results mean for MR–based learning. Drawing on the quantitative and qualitative findings presented in Chapter 6, I first interpret where the MR anatomy prototype appeared to improve students' experience and performance, where its impact was more limited, and why these patterns emerged. Summary statistics for all Likert-scale items referenced in this chapter are reported in Table 6.5 in Chapter 6. I then translate these patterns into design implications for future MR educational tools and relate them to prior AR/MR work discussed in Chapter 2. Finally, I outline key limitations of the current study and prototype and describe directions for future work.

## 7.1. Improvements, Limitations, and Explanatory Factors

The quantitative and qualitative findings from Chapter 6 are interpreted in this section to describe what appeared to improve when students used the mixed reality (MR) prototype, what did not change as much as expected, and why these patterns emerged. The discussion draws on the short-answer test results (Section 6.2), the Likert survey (Section 6.3), and the five qualitative themes from reflection responses and observation notes (Section 6.4).

Overall, the Likert survey results show that this small group of nursing students perceived the MR prototype as highly engaging, supportive of understanding and spatial reasoning, and promising for future nursing education, with only minor issues related to interface consistency. High scores on enjoyment and perceived educational potential support the minor but positive differences between paper and MR test accuracy reported in Section 6.2, and they provide a quantitative bridge to the qualitative reflections and theme-based analysis presented in Section

6.4. At the same time, Section 6.2 also showed that gains on the MR-based short-answer test were modest and varied by system and by item. This pattern suggests that part of the constraint on score differences between the paper and MR tests reflects a mismatch between the most difficult test items and the specific content emphasized in the prototype, rather than a lack of learning across the session. This alignment issue is revisited in Section 7.3 when discussing limitations of the assessment design and alignment between learning objectives, MR activities, and outcome measures.

Despite these constraints on measured gains, the qualitative and Likert results pointed to several areas where students clearly felt the MR prototype helped. Starting with the first major area of improvement, which concerned spatial understanding and the ability to reason about three-dimensional relationships. Spatially focused Likert items were rated very highly: Statement 1 ("The Mixed Reality experience helped me better understand the anatomical system compared to traditional 2D materials") and Statement 2 ("The 3D visualization made it easier to remember the spatial relationships between anatomical structures") had mean ratings of 4.75 out of 5, and Statement 4 ("The Mixed Reality experience encouraged me to think more critically about how the body's systems interact") had an even higher mean of 4.875. These ratings align with participants' reflections in Section 6.4.1, where they described using rotation, depth, and movement around the model to examine anatomical relationships, often relying on visual landmarks and even mid-air gestures to reason through questions during the MR-based test. For many students, the MR environment did not simply replicate the content of 2D diagrams; it made it possible to "walk through" the body in three dimensions in a way that felt easier to understand and remember. Thus, even if the short-answer scores did not show large numerical gains, students experienced a qualitative improvement in how they could see and organize spatial relationships.

A second area of improvement involved engagement and motivation. Engagement-focused Likert items were also strongly endorsed: Statement 5 (“I felt fully engaged while using the Mixed Reality platform”) had a mean rating of 4.75, and Statement 7 (“The immersive environment made the learning experience more enjoyable”) received a mean rating of 5.00, with every participant choosing the maximum rating. These quantitative patterns are consistent with the engagement and motivation theme in Section 6.4.2, where students described the MR session as fun, attention-grabbing, and better suited to their preferred ways of learning rather than ordinary study routines. They highlighted the novelty of the headset, the sense of being “cool” or excited while studying, the physical act of standing and moving around the model, and the feeling that the content was right in front of them and hard to ignore. Taken together, these comments indicate that MR improved not only how students could view the content but also how invested and focused they felt while working with it.

The third theme, perceived learning and confidence, helps explain why students rated the platform so positively despite modest test-score changes. Likert items that targeted learning and confidence received high ratings: Statement 3 (“Using the Mixed Reality model improved my confidence in explaining how this system functions”) had a mean of 4.25, indicating generally positive but somewhat cautious agreement, while Statements 1 and 2 again showed means of 4.75. Statement 9 (“The Mixed Reality platform has potential to improve how nursing students learn complex concepts”) also had a mean rating of 4.875. Together, these numbers suggest that students believe the platform supports their understanding and has strong potential to help with complex material, even if they were somewhat cautious about claiming that a single short exposure had fully transformed their ability to explain every system. As described in Section 6.4.3, participants frequently stated that MR would help them “do better” in anatomy and physiology, remember structures more clearly, and feel more confident in their understanding of key systems. Thus, perceived learning and confidence appear to have improved more strongly at a subjective level than was captured by the limited, single-session short-answer tests.

Not everything improved equally, however. The usability and interaction findings show that the interface, while generally well received, still introduced friction that may have limited the depth of learning students could achieve in one session. On the Likert survey, Statement 6 (“The controls and interface of the Mixed Reality system were intuitive and easy to use”) had a mean rating of 4.625 out of 5, indicating that most participants agreed that the interaction model was intuitive overall, although one participant selected a more cautious rating of 3. Reflection comments, summarized in Section 6.4.4, clarify that this lower rating was driven by intermittent issues with pinch gestures and left-hand responsiveness rather than confusion about what the controls were intended to do. Conversely, participants who rated this item more highly emphasized that any difficulties were due to getting used to pointing and pinching in mid-air and would likely decrease with practice. Students generally felt that the interface was learnable and intuitive, with a short but noticeable adjustment period around mid-air gestures, hand tracking, and field-of-view constraints. Minor glitches could temporarily disrupt the experience, and although participants framed these issues as fixable implementation details rather than reasons to avoid MR altogether, the interruptions likely consumed time and attention that could otherwise have been invested in exploring the content.

Finally, the future-oriented ratings on the Likert survey and additional comments provide insight into what students believed MR could improve beyond the specific anatomy content used in this study. On the Likert survey, Statement 8 ("I would prefer to use Mixed Reality for other nursing or healthcare topics in the future") had a mean rating of 4.625, and Statement 9 again showed a mean of 4.875, indicating strong enthusiasm for using MR with additional, more complex topics. These high ratings suggest that students not only viewed MR as helpful for the specific systems covered in this study but also saw strong potential for expanding the platform to other complex nursing topics. In Section 6.4.5, students described potential applications in pre-clinical simulation, surgical planning, and patient education, and requested features such as richer animations, multi-layer views, disease-specific changes, and integrated explanations. These reflections suggest that students saw the prototype as a promising foundation rather than a complete solution.

Taken together, these patterns indicate that the MR prototype primarily improved students' sense of spatial understanding, engagement, and perceived learning, while measured test gains were constrained by assessment alignment and some residual usability friction. The next section translates these observations into concrete design implications for future MR educational tools.

## 7.2. Design Implications for MR Tools and Alignment with Prior Work

After describing what changed for participants and why in Section 7.1, I distill those patterns into design implications for future MR educational tools in this chapter. The goal is not to repeat the results, but to translate the spatial, engagement, perceived learning, usability, and future application themes into practical guidelines for designing MR experiences in nursing and related domains. These design implications also respond directly to the gaps identified in Chapter

2, where most existing AR/MR systems are implemented as single-purpose, standalone prototypes rather than modular, reusable frameworks.

First, the strong emphasis students placed on depth, multiple viewpoints, and "walking around" the models suggests that MR tools should be intentionally built around 3D spatial exploration rather than treating it as a simple visual upgrade to 2D diagrams. Participants in this study relied on rotating the models, changing their point of view, zooming in on deeper structures, and using neighboring organs as reference points when answering questions. These observations suggest several guidelines for designing future MR applications: models should be easy to grab, rotate, and inspect from different angles; key structures should be visually emphasized as orientation cues; and models should be anchored in the room to allow learners to move around and "through" the model to view structures from multiple perspectives. In other words, the interface should make it straightforward for learners to move themselves and the model in ways that clarify "where things are" and how systems relate in space. This emphasis on interactive 3D spatial exploration is consistent with AR/MR studies in engineering education, where 3D structural models have been used to help students reason about complex systems and kinematics (see Section 2.3.2).

Second, participants' descriptions of the MR session as "fun," "cool," and highly engaging highlight the importance of designing for sustained engagement and motivation, not just novelty. Students reported that being immersed in the scene, standing up, and having the content "right in front" of them made it "harder to ignore" compared to reading slides or notes. Future MR educational tools can take advantage of this by presenting content in a way that fills the learner's immediate visual field and encourages movement around the model, while still allowing them to remain oriented in a familiar room. At the same time, the reflections suggest that MR was most appealing when it felt like a different, more active way to study rather than students' usual study routines. Structuring MR activities as focused, interactive sessions with goal-directed tasks, rather than as passive demonstrations, may help maintain the kind of attention and motivation students described. This design focus is consistent with general education reviews, which report that well-designed AR lessons can improve engagement and learning gains across STEM subjects, particularly when activities are aligned with clear instructional goals rather than relying solely on initial excitement (see Section 2.3.3).

Third, the perceived learning and confidence findings, together with students' feature requests, points toward the need for MR tools that connect 3D visualization to guided explanations. Participants frequently suggested that a tool like this would have improved their performance in anatomy and described MR as a better fit for how they learn rather than traditional teaching methods. At the same time, they asked for more help in understanding function and pathology, including additional animations, disease-specific visualizations, and the ability to click an organ label to see what it does and what conditions are associated with it. These comments imply that future MR systems should pair 3D models with integrated explanations, rather than relying on separate materials. Doing so would align the tool more closely with the kinds of reasoning (e.g., "what this does" and "what happens when it goes wrong") that nursing students must perform.

Fourth, the usability and interaction findings underscore that even when students view technology as intuitive overall, gesture-based controls can introduce friction that competes with learning. Participants generally felt comfortable after some practice, but they described a learning curve with mid-air pinching and occasional issues with hand tracking, especially for the left hand, as well as moments when content moved or tilted unexpectedly or drifted out of view.

It is also important to note that this study used the HoloLens 2, which is now a relatively mature device; as MR hardware and tracking algorithms continue to advance, many of these gesture-recognition and stability issues are likely to decrease. Future MR educational tools should therefore consider the time for learners to practice core gestures, offer clear feedback when an interaction has succeeded or failed, and minimize situations where small tracking glitches cause large, unintended movements of the content. In this study, students often framed these problems as “user error” or solvable technical issues, yet the same comments make it clear that such interruptions still cost time and attention that might otherwise have been devoted to the material itself. Designing smoother, more forgiving interactions is thus an important part of enabling deeper learning, not just improving usability in isolation. These observations mirror recurring themes in AR/MR reviews for general education, which highlight device and tracking limitations, software bugs, and the risk of cognitive overload when interfaces are not carefully designed (see Section 2.3.3).

Finally, participants’ ideas for future nursing applications and requested features point toward designing MR frameworks that scale beyond a single anatomy prototype. Students imagined using similar tools for pre-clinical simulations (e.g., virtual patients they could assess and make mistakes on safely), surgical planning and intraoperative guidance, and patient education. They also suggested multi-layer views, larger “zoomed-in” submodels for complex structures, and condition-specific overlays that show how disease alters normal anatomy. Together, these suggestions imply that MR educational tools should be designed with modular content and scenarios in mind, so that the same underlying framework can support anatomy review, simulated clinical encounters, and patient-facing explanations by toggling different layers, animations, and explanatory overlays. These design priorities align with existing MR applications in patient care, prosthetic training, surgical planning, and professional education, and they directly address the need for modular, reusable MR frameworks identified in the literature (see Section 2.5).

## 7.3. Limitations and Future Work

As an early pilot study and first deployment of the mixed reality anatomy prototype, this study has several limitations that constrain how broadly the findings can be generalized. At the same time, the platform highlights several promising directions and practical considerations for future work. At the study level, the evaluation was conducted with a small sample of eight nursing students from the same university and program, all of whom had relatively recent anatomy coursework and similar academic backgrounds. This limits statistical power and makes it difficult to draw strong conclusions about how the platform would perform with larger and more diverse cohorts. In addition, each participant only completed a single MR session, so the dataset primarily reflects immediate impressions and short-term performance rather than long-term retention or consistent use of MR as part of ongoing study routines.

The assessment design also introduces constraints on how the quantitative results should be interpreted. As discussed in Chapter 6, several of the most challenging short-answer items targeted detailed pathophysiology or hormonal feedback relationships that were only partially represented in the MR content, and these items likely pulled overall averages downward. The paper-based and MR-based tests were administered in different media and focused on the same underlying concepts but not identical visual experiences, making the paper–MR score difference only a rough indicator of learning. Together, these factors mean that the modest gains observed on the MR test should be interpreted as preliminary and dependent on the alignment between the assessments and the MR content, rather than as a definitive measure of the platform's impact on achievement.

There are also limitations in how the qualitative data was analyzed. The mixed-methods results in Chapter 6 are based on a small set of reflection responses, Likert comments, and observation notes that were coded and synthesized manually to derive the five themes on spatial understanding, engagement, perceived learning, usability, and future applications. While this approach provided context-specific insight into how students experienced the MR session, it did not make use of dedicated computer-assisted qualitative data analysis software (CAQDAS) such as ATLAS.ti, which can support more systematic code management, retrieval, and documentation of analytic decisions. In future work, incorporating tools like ATLAS.ti with a larger set of participant data could help strengthen the qualitative analysis by supporting more systematic coding, easier retrieval of coded segments, and clearer documentation of participant quotes.

At the level of the prototype and hardware, the current system also has important constraints. The content used in the study covers a limited subset of anatomical systems and emphasizes high-level structures and relationships rather than a full library of detailed anatomy and pathophysiology states. As participants pointed out in their comments, the prototype does not yet include all of the features they envisioned, such as multi-layer views, disease-specific overlays and animations, and integrated textual explanations attached to each organ. Moreover, the application was deployed exclusively on the Microsoft HoloLens 2, which, while well suited to early MR prototyping, has a constrained field of view and relies on mid-air hand tracking and pinch gestures that occasionally failed or caused content to move out of view. These device-level limitations, along with the small number of models and animations, mean that the present implementation should be viewed as an initial proof-of-concept rather than a complete curricular platform.

Building on these foundations, several extensions are planned. Within healthcare education, a first priority is to expand the anatomical content and deepen the physiological representations. Drawing on faculty input and student feature requests, future iterations of the platform can add more detailed models of individual organs (such as the heart and lungs), along with animations that illustrate normal physiological processes and side-by-side views that depict how disease processes alter these structures over time. Linking labels directly to concise explanations of function and common pathologies would also make it possible for students to integrate exploring where structures are located, what they do, and what happens when they are disrupted.

Another planned extension is to leverage the modular architecture of the system to support cross-disciplinary deployments in engineering education. Because the current application separates the user interface and interaction logic from the underlying 3D models, the same interaction patterns can be reused with different content. In engineering contexts, for example, students could use an adapted version of this framework to examine deconstructed views of mechanical assemblies or trace current distribution in electrical circuits, all while interacting with a familiar interface. Over time, implementing these modules in introductory engineering courses would test the extent to which the design principles derived from the nursing study generalize to other STEM domains.

A third direction for future work involves refining the prototype's usability and interaction design in response to the findings reported in Chapters 6 and 7. This includes improving gesture handling and visual feedback so that small tracking errors do not produce large, unexpected movements of the models, streamlining the orientation tutorial to help students become comfortable with mid-air gestures more quickly, and adjusting the layout and behavior of on-screen controls to reduce unnecessary movement of the models and simplify basic actions. As newer MR hardware with improved tracking and wider fields of view becomes available, the same application logic can be migrated to take advantage of more stable hand tracking and more immersive visual presentation, which should further reduce interaction friction.

Finally, future work will focus on integrating the MR platform with existing instructional tools and evaluating it on a larger scale. Integrated workflows that connect the headset-based experience to tools such as the Anatomage table or high-fidelity simulation mannequins could allow students to move between whole-body visualizations and immersive 3D exploration within a single learning sequence. In the longer term, extensions into prosthetics education, such as visualizing prosthetic movement and function, could build on current MR applications in prosthetic training and feedback. Across these deployments, larger and more diverse samples, multiple sessions per participant, better alignment between MR activities and assessment items, and more systematic qualitative analysis will be essential for moving from the present exploratory pilot toward a validated, scalable MR framework that can bridge healthcare and engineering education through shared interaction patterns and reusable components.

# Chapter 8 – Conclusion

In this thesis, I set out to address a persistent challenge in healthcare education by helping students better visualize and make sense of complex concepts that are typically presented in static, two-dimensional materials that do not fully support spatial understanding. Within this context, most existing mixed reality applications in healthcare are designed as topic-specific applications with relatively little work on reusable frameworks that can be adapted across courses or disciplines. In response to this gap, I worked with faculty in Nursing, Life Sciences, and Exercise Science to design the Systems Simulation mixed reality framework, implement an MR anatomy prototype for the HoloLens 2, and evaluate its use with nursing students using a mixed-methods study. The central problem was how to create and assess a MR framework that could support students' spatial understanding of core healthcare content while remaining modular enough to be extended beyond a single prototype.

Three main contributions toward that goal are made in this thesis. First, I document a requirements-gathering process with stakeholders across multiple programs and translates their needs into specific use cases for an MR learning platform, particularly around visualizing spatial relationships in complex anatomical and healthcare-related systems. Second, I present the design and implementation of the Systems Simulation application itself, including an extensible architecture that separates content from interaction logic, reusable user interface patterns, and an initial library of anatomical models and animations packaged as an MR anatomy prototype for nursing education. Third, I report a mixed-methods pilot evaluation with eight nursing students that combines short-answer assessments administered on paper and within the MR session, Likert-scale ratings of multiple facets of the MR experience, and qualitative data from reflections and observation notes. Together, these contributions move beyond an isolated MR demonstration driven primarily by novelty or a “wow” factor toward a documented and flexible framework with initial evidence for its use in healthcare education.

The evaluation provides preliminary but meaningful evidence about how this kind of MR framework can affect nursing students’ learning experiences. On the short-answer tests, most participants performed as well or better when answering questions within the MR session compared to the paper-based test, although the overall gains were modest and constrained by partial misalignment between some assessment items and the MR content. In contrast, students’ self-reported perceptions were strongly positive as they rated the MR session highly for improving their understanding of three-dimensional relationships, reported feeling more engaged and confident while working with the models, and expressed a strong preference for using MR to study similar topics in the future. Qualitative themes, developed from participant data and considered alongside prior work, reinforced these patterns. Students described walking around the models, using neighboring structures as landmarks, and recalling spatial layouts that they had found confusing in traditional materials. At the same time, they reported moments of usability friction, such as head-tracking glitches and a learning curve for the hand-based interactions, which occasionally pulled attention away from the material.

These mixed results highlight the promise and the current limits of the study. On the one hand, the findings suggest that a carefully designed MR experience can meaningfully enhance students’ spatial reasoning, engagement, and perceived learning in ways that complement traditional instruction, even in a single-session deployment with a small sample. On the other hand, they emphasize that measurable achievement gains depend on close alignment between MR activities and assessment items, and that usability issues can get in the way of learning if gesture-based controls are not sufficiently stable and forgiving. The design implications identified in this study point toward actionable ways to strengthen future iterations. These include centering interaction design on 3D spatial exploration rather than static viewing, pairing 3D models with integrated explanations of function, and refining handling and feedback so that interaction becomes a non-disruptive medium for studying rather than a hindrance to it

Looking ahead, the most lasting contribution of this work is not the specific anatomy prototype but the framework and design approach it demonstrates. By separating the user interface and interaction patterns from the underlying 3D content, the Systems Simulation application establishes a foundation that can be extended across topics and disciplines. Within healthcare education, this includes expanding the anatomical and physiological representations with additional animations, layering in disease states and explanatory overlays, and integrating the MR experience with existing tools such as the Anatomage table and simulation mannequins. Beyond healthcare, the same framework can be applied in engineering education to enable exploration of mechanical assemblies and electrical circuits, assist users with prosthetic devices, and support other complex systems that can benefit from interactive 3D visualization.

In summary, I demonstrate that a reusable mixed reality framework can be designed, implemented, and piloted in a real nursing course in ways that support students' spatial understanding, engagement, and perceived learning, while also highlighting important limitations that provide opportunities for further development. As the content library grows, the usability is refined, and the framework is deployed at a larger scale, such a platform has the potential to bridge multiple subject areas and allow students to see, manipulate, and reason about the complex systems they are studying. Although this work provides a starting point for a cross-disciplinary MR learning platform, future work should expand this approach and leverage the increasing availability of mixed reality devices to help shape the next generation of interactive learning experiences.

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# Appendix A

| Item | System | Structure | Question | Expected Answer |
|---|---|---|---|---|
| 1 | Circulatory | Femoral Vein | State its oxygenation and direction of flow relative to the heart. | Deoxygenated; carries blood toward the heart from the lower limb. |
| 2 | Digestive | Small Intestine | State its primary function. | Nutrient absorption. |
| 3 | Endocrine | Pancreas | State the hormone it secretes and its primary function. | Insulin; lowers blood glucose. |
| 4 | Lymphatic | Spleen | State the primary function. | Filters blood; immune surveillance. |
| 5 | Muscular | Quadriceps | State the primary action. | Knee extension. |
| 6 | Nervous | Spinal Cord | Classify as CNS or PNS and name one role. | CNS; conducts pathways and mediates reflexes. |
| 7 | Respiratory | Trachea | Classify as conducting or respiratory and say whether gas exchange occurs. | Conducting portion; no gas exchange. |
| 8 | Urinary | Kidney | Name its functional unit. | Nephron. |

***Table A.1:*** *Version A short-answer anatomy test questions and scoring key*

| Item | System | Structure | Question | Expected Answer |
|---|---|---|---|---|
| 1 | Circulatory | Aorta | State its oxygenation and direction of flow relative to the heart. | Oxygenated; carries blood away from the heart to the body. |
| 2 | Digestive | Liver | Name the secretion/function that aids fat digestion and what it does. | Bile; emulsifies fats for digestion. |
| 3 | Endocrine | Adrenal gland | Name the pituitary hormone controlling it and the feedback type. | Controlled by ACTH; cortisol provides negative feedback. |
| 4 | Lymphatic | Thymus | State the primary function. | T-cell maturation. |
| 5 | Muscular | Hamstrings | State the primary action. | Knee flexion. |
| 6 | Nervous | Median nerve | Classify as CNS or PNS and name one disorder associated with it. | PNS; associated with carpal tunnel syndrome. |
| 7 | Respiratory | Lung | Where does respiration occur, and what happens to the alveoli in COPD (Chronic Obstructive Pulmonary Disease)? | Respiration occurs in the alveoli; COPD causes inflammation and destruction of elastic fibers in alveolar walls, forming large, irregular air spaces (bullae). |
| 8 | Urinary | Ureter | State the direction of urine flow it carries. | Carries urine from kidney to bladder. |

***Table A.2:*** *Version B short-answer anatomy test questions and scoring key*

**Circulatory System**

https://sketchfab.com/3d-models/circulatory-system-a46a7227a957442da30486b97547eaf5

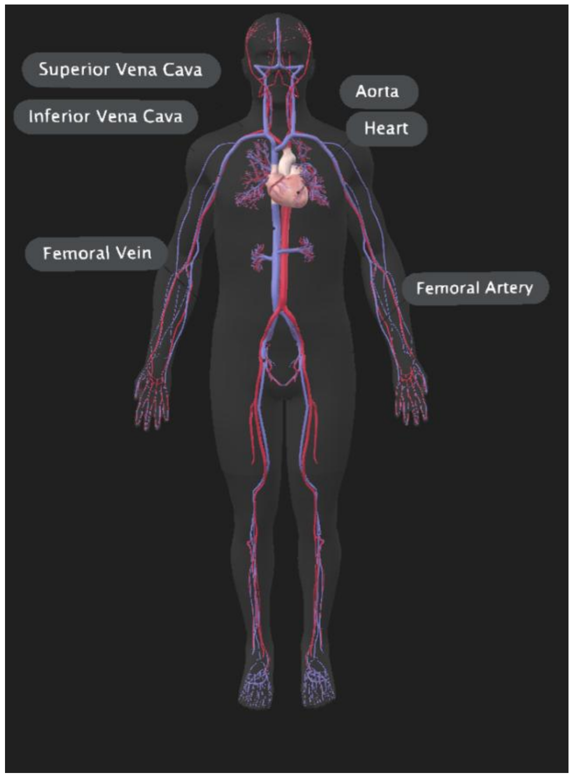


***Figure A.1:*** *Labeled Circulatory system model*

*Structures in Figure A.1:*

- Aorta
- Heart
- Femoral Artery
- Femoral Vein
- Superior Vena Cava
- Inferior Vena Cava

**Digestive System**

https://sketchfab.com/3d-models/digestive-system-2412d3f9bf17412db96b0718931a4efe

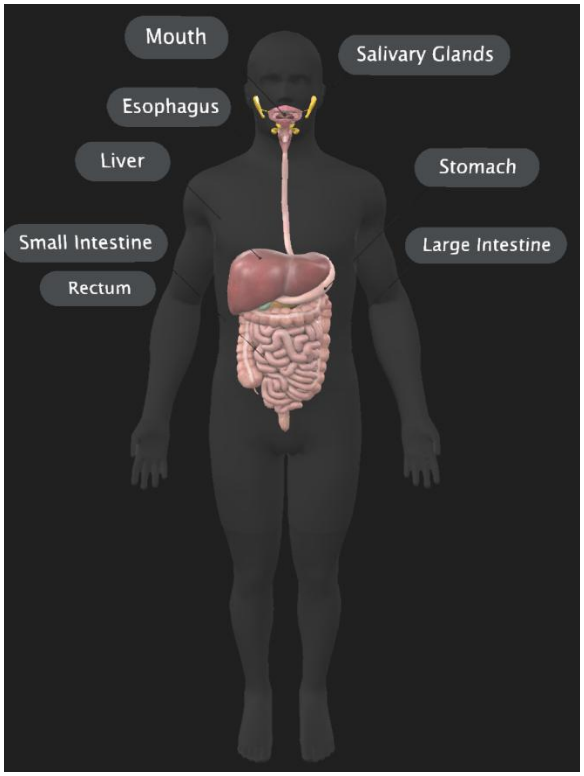


***Figure A.2:*** *Labeled Digestive system model*

**Structures in Figure A.2:**

- Esophagus
- Large Intestine
- Liver
- Mouth
- Rectum
- Salivary Glands
- Small Intestine
- Stomach

**Endocrine System**

https://sketchfab.com/3d-models/endocrine-system-b10f70cacb6946da851e5696291398a5

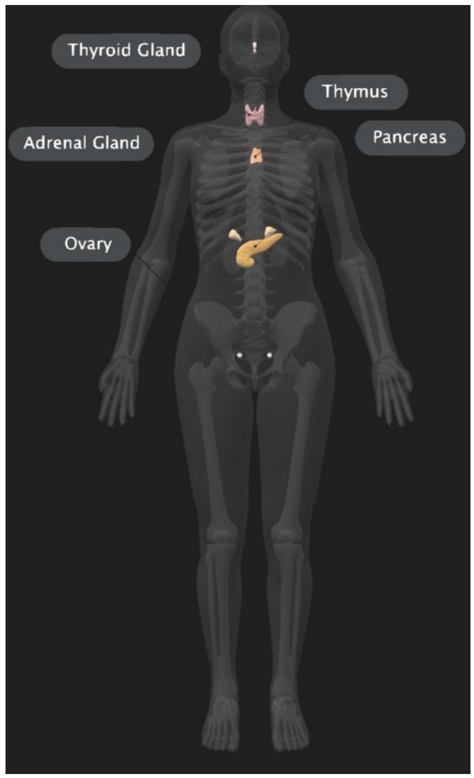


***Figure A.3:*** *Labeled Endocrine system model*

*Structures in Figure A.3:*

- Adrenal Gland
- Ovary
- Pancreas
- Thymus
- Thyroid Gland

**Lymphatic System**

https://sketchfab.com/3d-models/lymphatic-system-286b841af50143e58d4c5fcbfd41fbbe

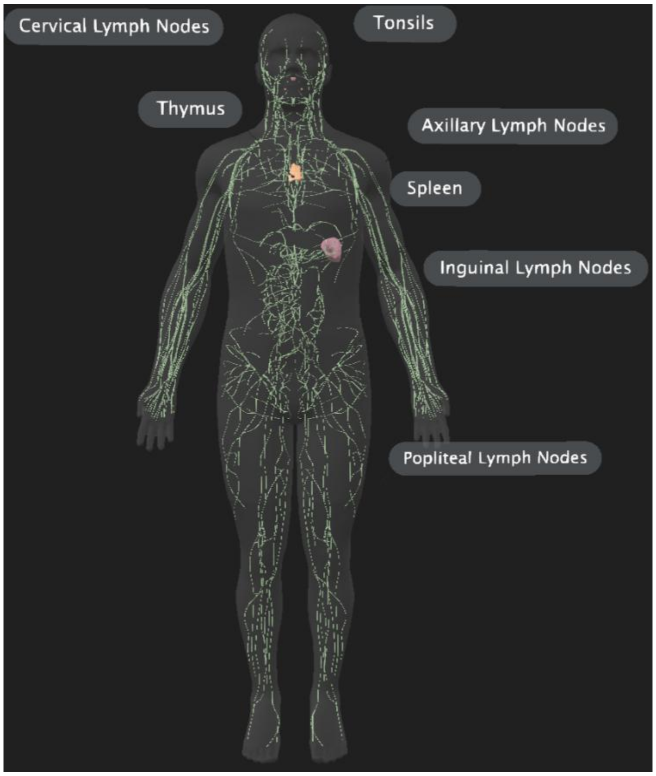


***Figure A.4:*** *Labeled Lymphatic system model*

*Structures in Figure A.4:*

- Axillary Lymph Nodes
- Cervical Lymph Nodes
- Inguinal Lymph Nodes
- Popliteal Lymph Nodes
- Spleen
- Thymus
- Tonsils

**Muscular System**

https://sketchfab.com/3d-models/muscle-system-d41e438f3bfa4da693ed0afda78f3631

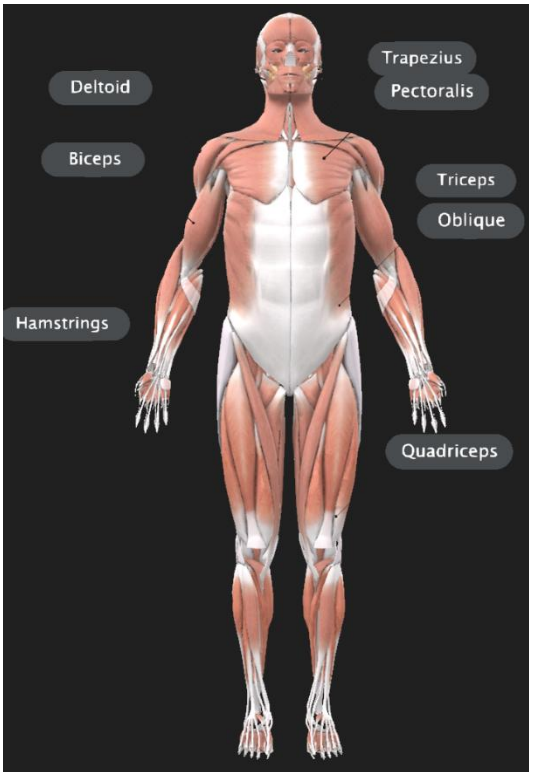


***Figure A.5:*** *Labeled Muscular system model*

*Structures in Figure A.5:*

- Biceps
- Deltoid
- Hamstrings
- Oblique
- Pectoralis
- Trapezius
- Triceps
- Quadriceps

**Nervous System**

https://sketchfab.com/3d-models/nervous-system-b4c0239fe0a34bbb92606f8a5248d0fa

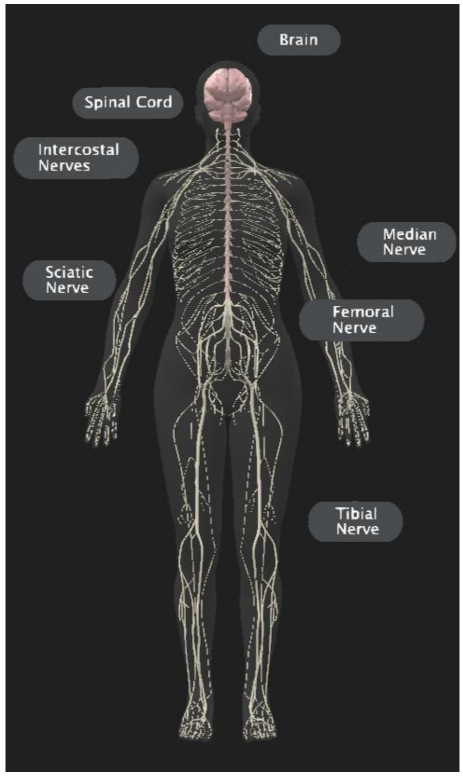


***Figure A.6:*** *Labeled Nervous system model*

*Structures in Figure A.6:*

- Brain
- Femoral Nerve
- Intercostal Nerves
- Median Nerve
- Sciatic Nerve
- Spinal Cord
- Tibial Nerve

**Respiratory System**

https://sketchfab.com/3d-models/respiratory-system-34ef811ecdd14eb99433daf26fcb8061

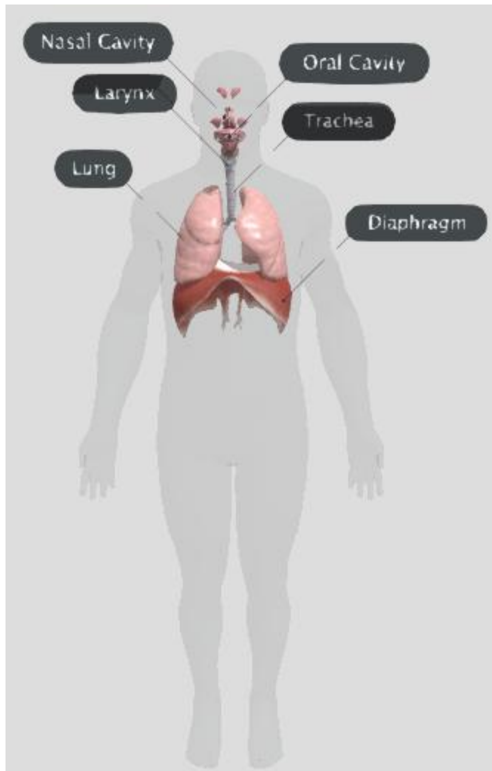


***Figure A.7:*** *Labeled Respiratory system model*

*Structures in Figure A.7:*

- Diaphram
- Larynx
- Lung
- Nasal Cavity
- Oral Cavity
- Trachea

**Skeletal System**

https://sketchfab.com/3d-models/skeletal-system-a16faac00e9944f7a80ed390844e221f

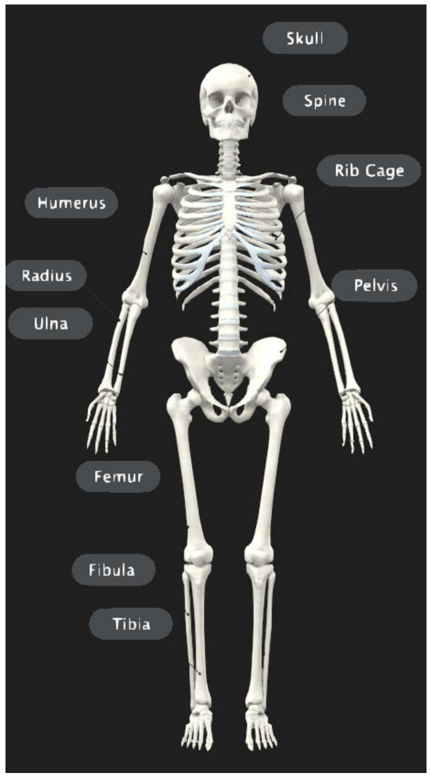


***Figure A.8:*** *Labeled Skeletal system model*

*Structures in Figure A.8:*

- Femur
- Fibula
- Humerus
- Pelvis
- Radius
- Rib Cage
- Skull
- Spine
- Tibia
- Ulna

**Urinary System**

https://sketchfab.com/3d-models/urinary-system-e400702200214c128ce25c6ea371f2b4

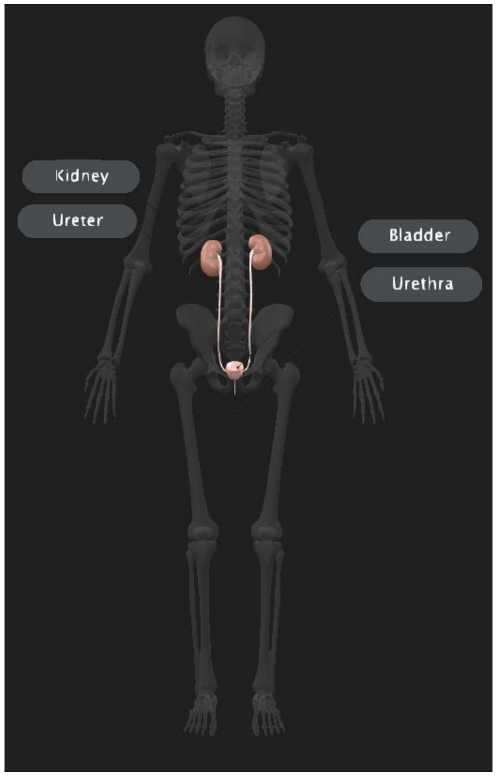


***Figure A.9:*** *Labeled Urinary system model*

*Structures in Figure A.9:*

- Bladder
- Kidney
- Ureter
- Urethra

**Pre-Recording and Consent**

[Before recording]

*Before we begin, would I have your consent to record audio and video for this session?*

[If the participant agrees: start recording audio and video.]

[Clap once to sync audio and video.]

*Can you please confirm for the camera that it is okay for me to record this session by putting a thumbs up?*

**Study Introduction**

*Hi! Thank you so much for volunteering to participate in my study today. My name is Ben, and I'm a graduate research assistant here in the Human-Centered Design Lab. I'm currently working on my thesis titled A Mixed Reality Platform for Interactive Learning in Healthcare Education.*

*The goal of this session is to explore how using Mixed Reality, basically 3D interactive visualization, might enhance how nursing students learn about complex body systems compared to traditional methods.*

**Confidentiality Reminder**

*Your responses will be kept completely anonymous and used only for research purposes in my thesis. If at any point you feel uncomfortable or want to stop participating, you can do so no questions asked.*

*I will first need you to fill out this questionnaire to the best of your ability.*

[Give participant demographic questionnaire and wait for them to fill it out]

**Session Overview**

*Today's session should take about 40 minutes total. You'll start with a short paper-based test to gauge your existing understanding of the topic.*

[Explain how paper-based test works and expectations for responses]

*Then, I will give you a brief tutorial on how to interact with this system.*

*After that, you'll use the Mixed Reality application, where you can interact with a 3D models of systems in which I will ask you similar questions and you would respond by pointing. I will not be able to see this part so please try to say as much as possible as it is recording your POV.*

*For both tests, I will not give you the correct answers after. Answer the questions to the best of the ability.*

*This isn't a graded activity, it's purely for research and educational purposes. I'm only interested in overall trends, not individual performance.*

[Mention the difficulty varies and they might not know some things to reassure them.]

*Finally, you'll complete a reflection questionnaire and some reflection questions, but it is going to be more of a conversation between us.*

**Before Starting Paper-Based Test**

*Lastly, I would like you to speak aloud whatever you are thinking as this experiment will only work with as much data as I can gather.*

[Ask if they have any questions prior to testing.]

*If not, we'll begin with the paper-test. Once that's done, I'll guide you through the Mixed Reality experience step by step.*

**During Tutorial**

*Please try not use the labels until after you respond to the question.*

***Figure A.10:*** *Session introduction script used with all participants*

# Appendix B

### Model Optimization Process

1. Download the source .glb or .gltf (Binary) file for the desired model.
2. Place the file into an Assets folder containing gltfpack.exe (from the meshoptimizer project: https://github.com/zeux/meshoptimizer/blob/master/gltf/README.md).
3. From the Visual Studio terminal (or a system terminal), change directory to the Assets folder and run:

```
.\gltfpack.exe -cc -tc -i ModelName.glb -o ModelName.opt.glb
```

where *ModelName.glb* is the original model and *ModelName.opt.glb* is the optimized output.

*Note:* For models with complex animations, gltfpack may not compress the file correctly. In these cases, StereoKit may fail to load the optimized file even though it is created without error, so the original (uncompressed) GLB was used instead.

### Code

***Systems Simulation* GitHub Repository:** https://github.com/bebadinia/HoloUWP

***Listing B.1:*** *Program.cs*

```
// Program.cs by Ben Ebadinia

using Scene;
using StereoKit;
using System;
using System.Reflection;

namespace HoloUWP
{
   class Program
   {

#if DEBUG
        static bool runOnce = true;       // Only exists in Debug builds
#endif

      static void Main(string[] args)
      {
       // Initialize StereoKit
       SKSettings settings = new SKSettings
       {
           appName = "Systems Simulation",
           assetsFolder = "Assets",
           //displayPreference = DisplayMode.MixedReality
       };

        if (!SK.Initialize(settings))
           Environment.Exit(1);

        SystemsModels.LoadAll();          // Load and Set all models once

        // Show main menu and set initial selection state (No button pressed)
        bool showUI = true;
        int startButtonPressed = 0;

        // Actual application loop
        SK.Run(() =>
        {
         // Checks to see if we should show the main menu or a system model
            if (showUI)
            {
             // Draw the main menu and check if button pressed
                int choice = LoadInterfaces.DrawStartInterface();

             // If a button was pressed, set the state to show that model
                if (choice != 0)
                {
                    startButtonPressed = choice;
                    showUI = false;             // Turn off the main menu
                    AppState.Anchored = false;  // Re-anchor model and
                }

            }
            else
            {
```

```
            // Decide which model is active, and draw it
               Model? active = null;

               // Select the model based on which button was pressed
               switch (startButtonPressed)
               {
                  case 1:
                  // Draw the circulatory system
                  // Check if labels should be shown based on AppState
                     active = AppState.ShowLabels ? SystemsModels.Circulatory
: SystemsModels.CirculatoryNL;
                     break;
                  case 2:
                  // Draw the digestive system
                     active = AppState.ShowLabels ? SystemsModels.Digestive :
SystemsModels.DigestiveNL;
                     break;
                  case 3:
                  // Draw the endocrine system
                     active = AppState.ShowLabels ? SystemsModels.Endocrine :
SystemsModels.EndocrineNL;
                     break;
                  case 4:
                  // Draw the lymphatic system
                     active = AppState.ShowLabels ? SystemsModels.Lymphatic :
SystemsModels.LymphaticNL;
                     break;
                  case 5:
                  // Draw the muscular system
                     active = AppState.ShowLabels ? SystemsModels.Muscular :
SystemsModels.MuscularNL;
                     break;
                  case 6:
                  // Draw the nervous system
                     active = AppState.ShowLabels ? SystemsModels.Nervous :
SystemsModels.NervousNL;
                     break;
                  case 7:
                  // Draw the respiratory system
                     active = AppState.ShowLabels ? SystemsModels.Respiratory
: SystemsModels.RespiratoryNL;
                     break;
                  case 8:
                  // Draw the skeletal system
                     active = AppState.ShowLabels ? SystemsModels.Skeletal :
SystemsModels.SkeletalNL;
                     break;
                  case 9:
                  // Draw the urinary system
                     active = AppState.ShowLabels ? SystemsModels.Urinary :
SystemsModels.UrinaryNL;
                     break;
                  default:
                     System.Diagnostics.Debug.WriteLine("Unknown button
pressed state");
                     break;
               }
```

```
             // If we have a valid model
             if (active != null)
             {
              // Draw the model interface and check if we should go back
                 bool goBack = LoadInterfaces.ModelInterface(active);

              // If user requested to go back, reset state to show main menu
                 if (goBack)
                 {
                     showUI = true;
                     startButtonPressed = 0;
                     AppState.Anchored = false;
                     System.Diagnostics.Debug.WriteLine("Going back to home
screen");
                 }

             // Boundary checking to find the chest height and offset for the
grab handle (based on human height)
#if false
Bounds HumanBounds = new Bounds(Vec3.Zero, new Vec3(0.6f, 1.8f, 0.6f));
Bounds HumanBounds= active.Bounds;
humanBounds.dimensions *= AppState.SystemScale * 1.05f; // a tiny padding
helps selection
UI.Handle("system-handle", ref AppState.SystemPose, HumanBounds);
UI.HandleEnd();
#endif

              // Lookup per-system config directly by the selected button id.
                 if (startButtonPressed != 0)
                 {
                     // Config for each system
                     var cfg = AppState.ChestAdj[startButtonPressed];

                     // Model-space bounds and chest point
                     Bounds HumanBounds = active.Bounds;
                     float totalHeight = HumanBounds.dimensions.y;
                     float bottomY = HumanBounds.center.y - totalHeight *
0.5f;
                     float middleF = cfg.chestF;     // fraction of height
                     float middleY = bottomY + totalHeight * middleF;

                     // Chest pivot in model space using manual local offset
                     Vec3 chestLocal = new Vec3(HumanBounds.center.x,
middleY, HumanBounds.center.z) + cfg.offsetLocal;

                     // One time anchor of the handle pose relative to the
Start Menu
                     if (!AppState.Anchored)
                     {
                      // Base of system relative to the Start Menu
                      // +X = right of the menu, +Y = up, -Z = in front
(toward the user), +Z = behind
                         Vec3 modelFromMenu = new Vec3(-0.75f, 0.00f, 0.50f);

                      // AnchorSystem: pose at menu + rotated offset, inherit
menu facing
```

```
                         AppState.SystemPose.position =
AppState.StartingWinPose.position + (AppState.StartingWinPose.orientation *
modelFromMenu);
                         AppState.SystemPose.orientation =
AppState.StartingWinPose.orientation;

                      // Anchor Model UI making it the same as Start window
                         AppState.ModelWinPose.position =
AppState.StartingWinPose.position;
                         AppState.ModelWinPose.orientation =
AppState.StartingWinPose.orientation;

                         AppState.Anchored = true;
                     }

                     // Bounds of the model relative to the chest pivot
                     Bounds handleBounds = new Bounds(
(HumanBounds.center - chestLocal) * AppState.SystemScale,   // center offset
HumanBounds.dimensions * AppState.SystemScale * 1.01f);     // tiny padding

                     // Grabbable handle with adjusted grab point
                     UI.Handle("system-handle", ref AppState.SystemPose,
handleBounds);


                     // Draw model offset so visuals stay aligned under the
chest pivot
                     Matrix modelXform = Matrix.TRS(
 AppState.SystemPose.position - (AppState.SystemPose.orientation *
(chestLocal * AppState.SystemScale)), AppState.SystemPose.orientation,
AppState.SystemScale);

                     // Finally draw the active model
                     active.Draw(modelXform);
                 }
             }

          }

       });
     }
   }
}
```

***Listing B.2:*** *AppState.cs*

```
// AppState.cs by Ben Ebadinia

using System.Collections.Generic;
using StereoKit;

namespace Scene
{
    public static class AppState
    {
        //Interfaces
        public static Pose StartingWinPose = new Pose(0, 0, -0.5f,
Quat.LookDir(-Vec3.Forward));
        public static Pose ModelWinPose = new Pose(-0.25f, 0, -0.5f,
Quat.LookDir(-Vec3.Forward));

        //Models
        public static Pose SystemPose = new Pose(0, 0, -1f, Quat.LookDir(-
Vec3.Forward));

        // Model/UI placement state so we only anchor once
        public static bool Anchored = false;

        //Main Scale for Models
        public static float SystemScale = 1.0f;

        // Adjustments to re-anchor the handle at the chest
        // chestF:     fraction of height for chest (0=feet, 1=head)
        // offsetLocal:fine tweak in MODEL space (meters), e.g. nudge
forward/up
        // lineOffset: shift guide line left/right in MODEL +X (meters)
        public static Dictionary<int, (float chestF, Vec3 offsetLocal)>
ChestAdj = new Dictionary<int, (float, Vec3)>
        {
            { 1, (0.75f, new Vec3(0.02f, 0.01f, -0.1f)) },  // Circulatory
            { 2, (0.75f, new Vec3(0.01f, 0.01f, -0.1f)) },  // Digestive
            { 3, (0.75f, new Vec3(-0.05f, 0.01f, -0.1f)) }, // Endocrine
            { 4, (0.75f, new Vec3(0.08f, 0.01f, -0.1f)) },  // Lymphatic
            { 5, (0.75f, new Vec3(-0.03f, 0.01f, -0.1f)) }, // Muscular
            { 6, (0.75f, new Vec3(0.03f, 0.01f, -0.1f)) },  // Nervous
            { 7, (0.75f, new Vec3(0.07f, 0.01f, -0.1f)) },  // Respiratory
            { 8, (0.75f, new Vec3(-0.05f, -0.04f, -0.1f)) },// Skeletal
            { 9, (0.75f, new Vec3(0.03f, 0.01f, -0.1f)) },  // Urinary
        };

        // Animation state
        public static int SelectedAnim = 0;
        public static bool LoopAnim = false;

        // Label state
        public static bool ShowLabels = false;

        //Reset to defaults
        public static void Reset()
        {
```

```
             //StartingWinPose = new Pose(0, 0, -0.5f, Quat.LookDir(-
Vec3.Forward));
            // Base of system relative to the Start Menu
            // +X = right of the menu, +Y = up, -Z = in front (toward the
user), +Z = behind
            Vec3 modelFromMenu = new Vec3(-0.75f, 0.00f, 0.50f); // tweak to
taste

            // AnchorSystem: pose at menu + rotated offset, inherit menu
facing
            AppState.SystemPose.position = AppState.StartingWinPose.position
+ (AppState.StartingWinPose.orientation * modelFromMenu);
            AppState.SystemPose.orientation =
AppState.StartingWinPose.orientation;

            // Anchor Model UI making it the same as Start window
            AppState.ModelWinPose.position =
AppState.StartingWinPose.position;
            AppState.ModelWinPose.orientation =
AppState.StartingWinPose.orientation;
            SystemScale = 1.0f;
            SelectedAnim = 0;
            LoopAnim = false;
            ShowLabels = false;
            // important: allow re-anchoring next time
            Anchored = false;
        }
    }
}
```

***Listing B.3:*** *LoadInterface.cs*

```
// LoadInterface by Ben Ebadinia

using StereoKit;
using System.Xml.Linq;

namespace Scene
{
    public static class LoadInterfaces
    {
        // Draw the starting interface and return the selected system index
        public static int DrawStartInterface()
        {
            // Start result as 0 (no selection)
            int result = 0;

            // Begin the main window at the stored pose
            UI.WindowBegin("Main Window", ref AppState.StartingWinPose);

            UI.Label("Welcome to the Mixed Reality Experience!");
            UI.Label("Choose a system to explore:");

            // Buttons for each system - set result accordingly
            if (UI.Button("Circulatory System"))
            {
System.Diagnostics.Debug.WriteLine("Circulatory System button pressed");
                result = 1;
            }

            if (UI.Button("Digestive System"))
            {
System.Diagnostics.Debug.WriteLine("Digestive System button pressed");
                result = 2;
            }

            if (UI.Button("Endocrine System"))
            {
System.Diagnostics.Debug.WriteLine("Endocrine System button pressed");
                result = 3;
            }

            if (UI.Button("Lymphatic System"))
            {
System.Diagnostics.Debug.WriteLine("Lymphatic System button pressed");
                result = 4;
            }

            if (UI.Button("Muscular System"))
            {
System.Diagnostics.Debug.WriteLine("Muscular System button pressed");
                result = 5;
            }

            if (UI.Button("Nervous System"))
            {
System.Diagnostics.Debug.WriteLine("Nervous System button pressed");
```

```
                result = 6;
            }

            if (UI.Button("Respiratory System"))
            {
System.Diagnostics.Debug.WriteLine("Respiratory System button pressed");
                result = 7;
            }

            if (UI.Button("Skeletal System"))
            {
System.Diagnostics.Debug.WriteLine("Skeletal System button pressed");
                result = 8;
            }

            if (UI.Button("Urinary System"))
            {
System.Diagnostics.Debug.WriteLine("Urinary System button pressed");
                result = 9;
            }

            UI.WindowEnd();
            return result;
        }

 // Draw the model interface and return true if the back button was pressed
        public static bool ModelInterface(Model model)
        {
            // Begin the model window based on last position of main window
            UI.WindowBegin("Model Controls", ref AppState.ModelWinPose);

            // Back button to return to main interface
            if (UI.Button("◀  Back"))
            {
                System.Diagnostics.Debug.WriteLine("Go Back button pressed");
                UI.WindowEnd();
                AppState.LoopAnim = false; // Reset loop state when going
back

                if (model.ActiveAnim != null)
                {
                    model.PlayAnim(model.ActiveAnim,  AnimMode.Once); // Stop
any active animation
                }

                AppState.ShowLabels = false;

                return true; // Indicate that the button was pressed
            }

            UI.HSeparator();

            // Scale slider for the model
            UI.Label("Scale: ");
            UI.SameLine();
            UI.HSlider("system-scale", ref AppState.SystemScale, 0.2f, 1.0f,
0.1f, 0.15f);
```

```
            UI.HSeparator();

            // Clamp selection just in case
            if (AppState.SelectedAnim < 0 || AppState.SelectedAnim >=
model.Anims.Count)
            {
                AppState.SelectedAnim = 0;
            }

            // Guard if the model has no animations
            if (model.Anims.Count == 0)
            {
                UI.Label("No animations found for this model.");
                //UI.WindowEnd();
                //return false;
            }
            else
            {
                UI.Label($"Animations ({model.Anims.Count}):");

                // Radio list of all animations (one selectable)
                for (int i = 0; i < model.Anims.Count; i++)
                {
                    bool isActive = (AppState.SelectedAnim == i);

                    // StereoKit radio pattern: UI.Radio("label", ref int
value, int id)
                    if (UI.Radio(model.Anims[i].Name, isActive))
                    {
                        AppState.SelectedAnim = i;
                        model.PlayAnim(model.Anims[i].Name, AppState.LoopAnim
? AnimMode.Loop : AnimMode.Once);
                    }
                }

                UI.HSeparator();

                // Loop toggle for the animation
                if (UI.Toggle("Loop", ref AppState.LoopAnim))
                {
                    // If an animation is already selected, restart it with
the new loop setting
                    if (AppState.SelectedAnim >= 0 && AppState.SelectedAnim <
model.Anims.Count)
                    {
                        string name =
model.Anims[AppState.SelectedAnim].Name;
                        model.PlayAnim(name, AppState.LoopAnim ?
AnimMode.Loop : AnimMode.Once);
                    }
                }

                // Play button for the selected animation
                if (UI.Button("▶  Play Selected"))
                {
                    string name = model.Anims[AppState.SelectedAnim].Name;
```

```
                    model.PlayAnim(name, AppState.LoopAnim ? AnimMode.Loop :
AnimMode.Once);
                }
            }

            UI.HSeparator();

            // Toggle for showing labels
            if (UI.Toggle("Labels", ref AppState.ShowLabels))
            {
                // If an animation is already selected, restart it with the
new loop setting
                if (AppState.SelectedAnim >= 0 && AppState.SelectedAnim <
model.Anims.Count)
                {
                    string name = model.Anims[AppState.SelectedAnim].Name;
                    model.PlayAnim(name, AppState.LoopAnim ? AnimMode.Loop :
AnimMode.Once);
                }
            }

            UI.HSeparator();

            // Reset Models button
            if (UI.Button("Reset Models"))
            {
                AppState.Reset();
            }

            UI.WindowEnd();
            return false; // Indicate that the back button was not pressed
        }
    }
}
```

***Listing B.4:*** *SystemsModels.cs*

```
// SystemsModels.cs by Ben Ebadinia

using StereoKit;
using System;
using System.Reflection;

namespace Scene
{
    public static class SystemsModels
    {
        public static Model Circulatory;
        public static Model Digestive;
        public static Model Endocrine;
        public static Model Lymphatic;
        public static Model Muscular;
        public static Model Nervous;
        public static Model Respiratory;
        public static Model Skeletal;
        public static Model Urinary;

        public static Model CirculatoryNL;
        public static Model DigestiveNL;
        public static Model EndocrineNL;
        public static Model LymphaticNL;
        public static Model MuscularNL;
        public static Model NervousNL;
        public static Model RespiratoryNL;
        public static Model SkeletalNL;
        public static Model UrinaryNL;

        public static void LoadAll() // Load all the models
        {
            System.Diagnostics.Debug.WriteLine("Loading Models");

            Circulatory = Model.FromFile("circulatorySystem.glb");
            Digestive = Model.FromFile("digestiveSystem.opt.glb");
            Endocrine = Model.FromFile("endocrineSystem.opt.glb");
            Lymphatic = Model.FromFile("lymphaticSystem.opt.glb");
            Muscular = Model.FromFile("muscularSystem.opt.glb");
            Nervous = Model.FromFile("nervousSystem.opt.glb");
            Respiratory = Model.FromFile("respiratorySystem.glb");
            Skeletal = Model.FromFile("skeletalSystem.opt.glb");
            Urinary = Model.FromFile("urinarySystem.opt.glb");

            CirculatoryNL = Model.FromFile("circulatorySystemNL.glb");
            DigestiveNL = Model.FromFile("digestiveSystemNL.opt.glb");
            EndocrineNL = Model.FromFile("endocrineSystemNL.opt.glb");
            LymphaticNL = Model.FromFile("lymphaticSystemNL.opt.glb");
            MuscularNL = Model.FromFile("muscularSystemNL.opt.glb");
            NervousNL = Model.FromFile("nervousSystemNL.opt.glb");
            RespiratoryNL = Model.FromFile("respiratorySystemNL.glb");
            SkeletalNL = Model.FromFile("skeletalSystemNL.opt.glb");
            UrinaryNL = Model.FromFile("urinarySystemNL.opt.glb");

            // Try to play the animations if they exist
```

```
            TryPlayFirstAnimation(Circulatory, AnimMode.Once);
            TryPlayFirstAnimation(CirculatoryNL, AnimMode.Once);
            TryPlayFirstAnimation(Respiratory, AnimMode.Once);
            TryPlayFirstAnimation(RespiratoryNL, AnimMode.Once);

            // Uncomment to show the different Nodes
            /*
            ModelNode node = Skeletal.RootNode;
            int depth = 0;
            while (node != null)
            {
                string tabs = new string(' ', depth * 2);
                System.Diagnostics.Debug.WriteLine(tabs + node.Name);

                if (node.Child != null) { node = node.Child; depth++; }
                else if (node.Sibling != null) node = node.Sibling;
                else
                {
                    while (node != null)
                    {
                        if (node.Sibling != null)
                        {
                            node = node.Sibling;
                            break;
                        }
                        depth--;
                        node = node.Parent;
                    }
                }
            }
            */
        }


        static void TryPlayFirstAnimation(Model m, AnimMode mode)
        {
            if (m.Anims.Count > 0)
            {
                for (int i = 0; i < m.Anims.Count; i++)
                {
System.Diagnostics.Debug.WriteLine($"Anim {i}: {m.Anims[i].Name}");
                }
                string name = m.Anims[0].Name;
System.Diagnostics.Debug.WriteLine($"Playing anim: {name}");
                m.PlayAnim(name, mode);        // <-- call ONCE
            }
            else
            {
System.Diagnostics.Debug.WriteLine($"No animations found on {m}");
            }
        }

    }
}
```