IMMUNOLOGY VIRTUAL REALITY
A NEW FANTASTIC VOYAGE
Immunology Virtual Reality (VR): Exploring Educational VR Experience Design for Science Learning

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Abstract
Immunology Virtual Reality (VR) project is an immersive educational virtual reality experience that intends to provide an informal learning experience of specific immunology concepts to college freshmen in the Department of Biological Sciences at Virginia Tech (VT). The project is an interdisciplinary endeavor between my collaboration between people from different domain areas at VT: Creative Technologies, Education, Biological Sciences, and Computer Sciences. This thesis elaborates on the whole design process of how I created a working prototype of the project demo and shares insights from my design experience.
Immunology Virtual Reality (VR): Exploring Educational VR Experience Design for Science Learning

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General Audience Abstract
Immunology Virtual Reality is an immersive educational virtual reality experience in which a user takes on the role of an immune cell and migrates to fight off pathogen invasions at an infection site in the human body. It explores levels of interactivity and storytelling in educational VR and their impact on learning.
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1 Introduction

The Immunology Virtual Reality project concludes my three year plus study in the Creative Technologies MFA program at Virginia Tech with a comprehensive integration of visual designs, 3D modeling and animation, game and virtual environment development and interdisciplinary collaboration. The design process of the project brought me an intense yet very rewarding learning experience that came close to my current design philosophy, that is, to design interactive 3D art with purposes. Specifically, I chose to use cutting-edge VR technology as a tool and medium to visualize and implement my design concepts and imaginations, with a focus on science education.

This thesis elaborates on every aspects of the project design and covers four topics: design motivation, design process, VR design for learning, conclusion and future work, sharing with audience lessons and takeaways learned from the project’s design process with my first-hand experience.
Design Motivation
My first motivation for this project came from a great interest in interdisciplinary research and collaboration. After I started my schooling in Creative Technologies, I gradually realized that applications of 3D modeling and animation are not only limited to 3D games and CG movies. Instead, they have much greater use when integrated into applications in other areas with specific purposes, for example, education, simulation, training, etc. I am particularly interested in using 3D models and animation in the area of science education because they provide a great way to visualize abstract science concepts and complex forms. For example, in terms of helping learners understand structures of a specific molecule in chemistry, a 3D model and animation allows the learners to view the molecule from various perspectives and reveals its complex structure, which is hard to see clearly through a 2D illustration.

Figure 1. Areas of interdisciplinary collaborations involved in the project
My second motivation came from a special programming course I took in the program in my first semester, which introduced me with Processing, a programming language designed specifically for visual artists and designers. With Processing, an artist can visualize his/her design concepts completely through coding and it became a cool way to create computer art. During the time when I was taking the class, I had tried several ways of using Processing for different design purposes. For example, I had used it to manipulate images to create some cool visual effects. I had also tried to use it to create interactive data visualization of everyday social media use. Processing gave me some fun to play with codes without any programming background. After having been introduced to Processing, I developed an interest in programming for interactions and finally decided to learn programming in a more serious way by coding with C# in a game engine, Unity.

Figure 2 & 3. Previous work created by Processing. Left: image manipulation, Right: data visualization of personal social media use
I developed the third motivation from my exposure to current VR technology and its abundant affordances that allow artists and designers to do a lot with their creativity. Personally, I see VR as a new medium or tool that allows me to realize and my design concepts with both visuals and interactions. Compared with static 3D models or pre-rendered 3D animations, I am more interested in creating a 3D virtual environment (VE) in which people can interact with virtual objects and do things with purposes. Throughout the years of my design practices and creative endeavors, I have been gradually shaping my design philosophy and believing that creating interactive 3D designs that serve for specific purposes is a goal of my current and future work. The immunology VR project just provided me with a great opportunity to experiment with my current design philosophy in a perfect way.
Design Process
This section covers three major components of the whole design process in the project: concept design, visual design, and interaction design. In the section, I elaborate on the details of each component and show step-by-step workflows and strategies to accomplish specific design purposes.

3.1 Conceptual Design
Conceptual design is the very early stage of this project, in which project goals, contents, visual styles, interactions, and other important parameters are articulated and defined. It is a very essential part of a design process. From my prior experience in UX/UI design, I knew from the very beginning that this stage could never be done in a haste and instead it needed to be done very thoroughly with as many details included as possible.

3.1.1 Immunology Concept
The idea of creating a virtual environment inside the human body was greatly inspired by an old sci-fi movie, Fantastic Voyage (1966), adapted from a classic sci-fi novel by Issac Assimov. The movie fascinated me in many ways, the novel environments inside blood vessels and body tissues that nobody has ever been to; the white blood cells from the human immune system that kill pathogens without mercy; the cool miniaturization technology that shrinks people and a submarine into cellular sizes.

With inspirations from the movie, I started the design of a game prototype for an immunology game in 2016 and created some 3D models of white blood cells and blood vessel environments. Later, my advisors Thomas Tucker and Dane Webster helped me connect with an immunology professor, Dr. Caroline Jones, from Department of Biological Sciences at Virginia Tech. Dr. Jones is very interested in bringing the game into her classroom instructions and use it as a supplementary instructional resource to help
her students better understand some abstract immunology concepts. We had several meetings about which immunology concept we wanted to embed into the game design so that the students can learn it. Later in 2017, I suggested changing the original gaming idea into a first-person user-controlled immersive virtual experience and we all liked the idea with cool immersive visuals that the VR technology provides. We went further to finalize the immunology concept to be embedded into the experience, that is, the neutrophil transmigration process and killing mechanisms. According to Dr. Jones, neutrophils are the most abundant white blood cells in the human immune system yet the least studied white blood cells. Their functions in the immune system are not fully understood by immunologists and many new discoveries have been coming out in recent years. Therefore, to create a virtual experience that focuses on the cell helps people to better understand those new discoveries of their functions.

Figure 5. Neutrophils’ transmigration process from blood vessels to site of infection.

Figure 6. Three different killing mechanisms used by neutrophils to eliminate pathogens in specific situations.
3.1.2 Scenarios

Once the immunology concept to be embedded into the experience is finalized, I started writing scenarios for the experience, which allowed me to go further to think about every detail of the experience, such as, visual representations of the neutrophils and the environments they live in, and interaction techniques a user employs to interact within the virtual environment (VE). Those scenarios helped me to visualize the whole interactive, virtual experience from every aspect of user experience design.

[Narrative] First person role play of a neutrophil

......The user immediately drops into the scene and finds himself inside a blood vessel in human body and around him are cells in different shapes, sizes, and colors. The user turns around and tries to familiarize himself with the VE by looking up and down and venturing his steps back and forward. An invisible virtual guide, Lexie, starts her narration in the user's earphone and instructs the user how to use controllers and contextual menus in the scene to navigate, select, and get necessary information for his actions. She will provide guidance and task assignments throughout the user's VR experience. The user is told that in the demo he will be taking the role of a certain type of white blood cell (neutrophil) in human immune system in a fully synthetic immersive virtual environment that resembles a microworld inside human body, somewhere in a blood vessel and somewhere in body tissues. The user will stay inside a cockpit within a neutrophil body and control it to fulfill its responsibilities in the VE to protect human body from pathogen invasions. Since the neutrophil is the first responder in human immune system, it develops various ways to kill pathogens effectively based on different stimulations and chemical information (chemoattractants) it receives from the body. In the demo, the user will get familiar with a transmigration process of the neutrophils that allows them to migrate to sites of infection in a short time and employ their major killing mechanisms to fight pathogens. The user will need to decide which killing mechanism is the most effective under certain situations and selectively use it. Information of neutrophils, pathogens, and other types of body cells will be accessed via interactions with them in the VE, in various forms like text, audio, imagery, and animation.

Once Lexie walks the user through introduction and system navigation, the user continues to the main part of the demo by confirming on a dialog box that he understands everything and feels comfortable to begin his microscopic journey.

......

(see Appendix for full scenario)
3.1.3 Storyboards
Creating storyboards helped me further visualize every aspect of visual designs in the experience, making it easier for the ensuing 3D assets creation process. It also helped me visualize how the specific 3D UIs I chose for the experience work step-by-step when the user interacts with them in the context. Storyboards at this stage serve as a great tool to further integrate the immunology concept into the 3D virtual environment to be created.

Figure 7. Storyboards of a visualized VR experience in the project
3.2 Visual Design
The visual design section here focuses mostly on my personal exploration of a 3D assets creation pipeline that allowed me to create a low-poly style for all the 3D models.

3.2.1 Stylized Low-poly Art
Low-poly art originally came from the early days of 3D computer animation and games when limited computing power of computer hardware restrained numbers of polygons rendered in 3D models. Therefore, 3D models with lower polygon count reduced rendering time and increased frame rate significantly than higher polygon count models. Today, with advances in technologies, low-poly count of a 3D model is not as strict as a rule in the old days. However, the minimalist look of low-poly 3D models has established itself as a distinguished art style that has been favored by many digital artists and indie game developers.

Figure 8. Using the lowest number of polygons results in a very minimalist look. Image source: Netdna.com
As a super fan of low-poly art, I decided to create all 3D assets in the virtual environment (VE) using this style due to following reasons: First, low-poly models require less computing power of the system, which is important for a smooth, no lagging VR experience. Lags in a VR experience may result in a break of presence, a sense of being there, and cybersickness so they need to be avoid as much as possible. Second, low-poly models don’t require much texturing work to look as realistic as real life objects and cut down creation time a lot. Third, low-poly art is popular in video games and many gamers are familiar with it, which may add some emotional bonds to the current virtual experience.

### 3.2.2 3D Low-poly Creation Pipeline

There are many different pipelines to create low-poly look 3D models and which pipeline to choose depends mainly on a 3D artist’s skillset of 3D programs. In my case, I have used Maxon Cinema4D in the past to create some low-poly renders. So I just decided to use it to create the low-poly look for my 3D models. However, I modified my past pipeline by adding other 3D programs into it and taking advantages of the unique features of each programs. So my enhanced pipeline allowed me to create a low-poly 3D model in a more efficient way with better looks. Specifically, I started a 3D asset modeling with Zbrush sculpting and created a rough look of the model in a much faster way than vertex to vertex modeling in traditional 3D programs. After I was satisfied with the look of high-poly sculpts in Zbrush, I exported the model and imported it into Cinema4D to reduce its polygon count and create the desired low-poly look. I then further imported the low-poly model into Autodesk Maya to create UVs for texturing, rig it, and animate it. At last, I used a texturing program, Substance Painter, to create a simple ambient occlusion map to enhance the look of the low-poly model that was just animated and ready to be imported into a game engine. With this pipeline, I
was able to take advantage of all 3D programs that I know and create low-poly look 3D assets in a short time. Attached figures below illustrate this process.

Figure 9. A workflow of creating low-poly 3D game assets for the project

Figure 10. Low-poly white blood cell characters in the project
Figure 11a & 11b. Low-poly environment in the project
3.3 Interaction Design
As a major step to make the 3D virtual environment (VE) alive and respond to the user inputs, the interaction design plays an essential role in the design process. Within a VE, a user needs to use controllers with 6 degrees of freedom (DOF: x, y, z for position and pitch, roll, yaw as rotation) to interact with virtual objects and receive their responses. One major design question is, how to create 3D UIs that are intuitive, easy-to-learn, and novel to the users so that their user experience won’t affect their task performance. To achieve that goal, I spent quite some time working with experts from the 3D interaction design area at Virginia Tech and I elaborate my experiences and design strategies below.

3.3.1 Design Spaces: 2D Versus 3D
With a background and prior experiences in UX/UI design, I started approaching the interaction design problem by looking into differences in designing with different dimensions, namely, 2D versus 3D. With a 2D mobile interaction design, the design space is confined to small size screens and a user can use different gestures to create interactions on the screen. For example, tap to confirm, scroll to move, pinch to zoom in or out, etc. Those gesture-based interactions on 2D screens were developed into design patterns that app interaction designers often use as references. One great advantage of using design patterns in screen-based interaction design is that most users are quite familiar with them. No matter what the purposes of an app, may it be a mobile game, or a specific application for online shopping, etc, as long as the user wants to confirm something, “tap screen” can always be the interaction gesture to achieve that goal. People are using mobile devices everyday and they are quite familiar with those interaction gestures. So they don’t need to spend time learning how to confirm something in a new app as long as it follows design patterns of established interaction gestures. Design patterns in 2D mobile interaction design are great ways to create consistent user experiences across different apps.

Figure 12. Mobile interaction design gesture patterns
However, in terms of interaction design in a 3D space, things are not that easy to set up and there are few design patterns to follow. 3D interactions in a VE is very much like the way people interact with objects in a real-life physical world. Once people establish their presence in a VE, a sense of being there, they would mostly expect to interact with virtual objects in the VE in similar ways that they do in the physical world. Any unnatural or poorly designed 3D UIs that hinder the natural flow of expected interactions in the VE would break the presence and result in non-credibility of the VE. Since people interact with objects in the physical world in many different ways, 3D interactions and their UIs in the VEs could also be in many ways. The following examples show several different 3D UIs for 3D interactions in VEs.

Figure 13. Using a hovercast slider menu to interact with virtual objects in 3D space.
As shown from examples, due to the nature of 3D interactions, their UIs can be designed in many, many different ways based on specific application needs and contexts. Therefore, it is very hard to come up with universal design patterns for 3D UIs that fit into different applications with minimum changes. In reality, most 3D UIs have been designed from the ground up based and only work the best in contexts where they are intended to be used.
3.3.2 Working with 3D Interaction Group at Virginia Tech

Having understood the difficulty in developing 3D UIs for interactions in the project, I started to look for resources that would help me with the development process of 3D UIs. Fortunately, there is a 3D Interaction Group (3DI) led by a distinguished 3D UI design researcher, Dr. Doug A. Bowman, here at the Computer Science Department, Virginia Tech and I was able to connect to Dr. Bowman through my advisor Dane Webster. To better understand every aspect of 3D UI designs, I first took a Virtual Environments (CS5754) class taught by Dr. Bowman and did some design practice in a class group project. After acquiring the basic skills of programming with C# in Unity game engine, I developed prototypes of 3D UIs in the project and met Dr. Bowman and his 3DI group regularly for design feedback and suggestions. During that time, I showed project-in-progress demos four times to gather information for design iterations, which I believe is an important part in every human-computer interaction design project. With Dr. Bowman’s design guidance and feedback from 3DI group (see Appendix for feedback details), the 3D UIs in my project gradually took shape and started to work as I expected.

Figure 16. Dr. Bowman (2nd row, 2nd right) and 3D Interaction group
3.3.3 Design Strategies for 3D Interaction in the Project

The 3D User Interfaces: Theory and Practice (Bowman, et al., 2017) suggests several design strategies for designing new 3D UIs and they can be briefly described below.

Borrowing from the real world: with this design strategy, designers create 3D UIs by replicating and adapting real-world interaction patterns. Specifically, using real-world metaphors is a very effective way to familiarize users with new 3D UIs because the users are already familiar with real-world artifacts, it is easy for them to understand the purpose and method of using 3D interaction techniques based on them. For example, a virtual vehicle metaphor has been one of the most often used metaphors for 3D navigation and travel and a virtual flashlight has been used to set viewpoint or lighting directions (Bowman, et al., 2017).

Adapting from 2D UIs: this design strategy allows designers to adapt 2D interaction techniques and connect them with 3D interactions because 2D UIs and interaction techniques have been thoroughly studied and design paradigms well established, and most users are already very familiar with them so learning can be kept to a minimum (Bowman, et al., 2017). For example, a 2D GUI can be placed and rendered on a polygon surface in a 3D environment and the user can interact with virtual buttons and menus arranged on a 2D plane in the environment.

Magic and Aesthetics: with this strategy, designers create 3D interaction techniques that allow a user to overcome human limitations in the real world and give him/her some “super power” to interact with virtual objects in the VEs. For example, a flying technique allows the user to fly from one place to another like birds within a VE and enhance his/her move-
ment, but is impossible to do in real-world. In addition, some of those magical interaction techniques were borrowed from fantasy and sci-fi movie metaphors from specific cultures, so if the user has had the knowledge of them before, it can be enjoyable to use them in the VEs.

Based on above-mentioned design strategies for 3D UI and interactions in the VEs, I worked with Dr. Bowman to specify which 3D UI design strategy is suitable for which 3D interaction in the project by considering several parameters directly related to the design, such as, learning goals of embedded concepts, technological limitations, user backgrounds, and novelty. Examples of 3D UI and interaction design in the current project are described below.

1. The cockpit metaphor
With this metaphor, I created a cockpit inside a neutrophil’s body that allows a user to interact with it and control the neutrophil’s movement inside the human body. The cockpit contains several displays and a joystick/weapon control panel and allows the user to receive system information and experience instructions throughout the whole experience. It also provides a visual reference to the user while he/she is moving virtually in the VE and helps reduce the possibility of cybersickness.

![Figure 18a. Pilots control an airplane inside its cockpit](image1)
![Figure 18b. A cockpit designed to control a neutrophil in the project](image2)

2. The chemokine sensor metaphor
This metaphor was designed based on one specific aspect from immunology concept embedded. In the concept, a neutrophil needs to detect and follow chemical information (chemokine) sent from a site of infection and that information eventually leads the neutrophil to reach the site of infection. So after discussion with Dr. Bowman, we came up with a UI design that somewhat resembles a metal detector in the real world, including a round visual gauge showing how far
the neutrophil is from the site of infection and a beeping sound that changes its tempo frequently based on distance to the site of infection (the closer the distance, the faster the tempo).

Figure 19a. Metal detectors in work

Figure 19b. Chemokine sensor to detect an infection site in the project

3. The gyrosphere metaphor
To visualize the rolling movement of a neutrophil on the surface of blood vessel, I borrowed a magic metaphor from the sci-fi movie, Jurassic World, the gyrosphere vehicle. With that metaphor, when the user moves its neutrophil body, he/she will see the neutrophil’s outer shell and some internal structures in movement and get a perception of being inside a rolling sphere.

Figure 20a. Gyrosphere metaphor from Jurassic Park (2015)

Figure 20b. The neutrophil body that a user controls in the experience
4. The Spiderman metaphor
In order to bring the users a fun, novel travel experience in the space between body tissues, a Spiderman travel metaphor was borrowed to create that magic 3D interaction effect. With the metaphor, the user shoots out a string to a nearby virtual object in the VE using a VR controller, just like Spiderman shooting out his spiderweb. Once the other end of the string attaches to the object, the user and the neutrophil body will be dragged towards that object as long as the user holds down the controller trigger.

Figure 21a. Spiderman shoots out spiderweb to move from place to place

Figure 21b. User uses a VR controller to shoot out a string at an object in experience
Design VR Experience for Learning

Applications of virtual reality for education have been in use by educators and researchers since the 1990s. However, many of those applications were just experiments and explorations of an alternative and novel instructional approach and few of them have been formally integrated as a part of in-classroom instructions due to limitations of the technology and learning subjects to be embedded. However, with the advances of recent VR technology, studies on the integration of VR applications into class curriculum have been on the rise and designing usable VR experiences to support effective learning is still an area many educators and researchers are interested in and applicable design principles and guidelines are sought-after by designers. This section first reviews a previous research on exploring principles of designing educational VEs and then elaborates on design guidelines that were specifically tailored to the context of current project and how they contributed to the project throughout the whole design process.

4.1 Previous Research on Design principles for Educational VEs

A study by Bowman, Gracey and Lucas (2004) has proposed four principles for designing educational virtual environments (VEs):

1. Interactivity: Educational VEs should provide students many opportunities to interact with and explore the environment, rather than simply offering a static visualization.
2. Complementarity: VEs should be used to complement, not replace, other methods of teaching and learning in the classroom.
3. Information-Richness: Educational VEs should contain many different types of information (geometric, textual, auditory, concrete, abstract, etc.).
4. Augmentation: Educational VEs will be most effec-
tive when they portray information that is not normally visible or accessible in the physical world.

These four principles suggested by Bowman et.al (2004) more than a decade ago still hold water for recent educational VR applications. Without interactivity, many people have found that a VR experience is just a visual tour in a 360 degree space and can get boring very soon. A common example is a lot of 360 videos that can be viewed in VR headsets. The interactivity provided by those videos is limited to changing of viewing positions or camera perspectives. In terms of complementarity, currently, educational VR applications are seen as alternative instructional approaches that have potentials in supporting traditional instructions in classrooms, which is an appropriate positioning of VR applications in educational context. Due to hardware limitations, not everyone is comfortable with a simulated experience produced in VR (e.g. motion sickness, eye strain, fatigue, etc.), a VR experience is recommended to be short and highly customizable. It can not fully replace traditional learning experiences for the time being. With the third principle, Information-richness, a user is exposed to various forms/modalities of information in VEs and that is a great way of stimulating mental processing of new information and building up long-term memories of new stimuli. The last principle, novelty, is also an important factor that engages people into exploring and learning new things. People are more interested in VR applications that provide them with experiences that they have never had before. For example, a trip to Mars or inside the human body. Educational VR apps should be selectable with their domain contents so that they can be interesting and engaging for learning.
4.2 Proposed Guidelines for Current Project

Based on the design principles from previous research, new guidelines were proposed to direct the design of the current research. Specifically, these new design guidelines include:

1. Rich interaction
The constructivist theory states that, knowledge is constructed by the individual through his or her interactions with the environment. And individuals gradually build their own understanding of the world through experience, maturation, and interaction with the environment, to include other individuals. A highly interactive VE provides a place where various forms of learning can take place. Interactions in the VEs take place in many ways: between a user and the environment, among multiple users, between users and other virtual objects, or even between virtual objects. In addition, those interactions can simulate both natural (real life metaphors) and hypernatural/magic (metaphors only exist in fictions or fantasies) situations for specific learning purposes. For example, in an educational VR experience about learning a forest ecosystem, a user can interact with plants and animals directly in the VE to retrieve information about them, an scenario that won’t happen in real life.

2. Information richness
As defined from previous research, information richness can be achieved through various formats of information input in the VEs. Although visuals are the dominant form of information input in the VEs, other forms of input, like audios and haptics are also important to keep a learner stimulated with new information. In the project, immunology concepts were conveyed to the users through several ways, such as, text and image information, audio instructions, and task performance.
3. Novel experience
Previous studies on VE design suggested that novelty plays an important role in keeping users engaged in a new environment that they haven’t been before. People have a tendency to explore new places and new things. A novel VE will also keep them staying longer and exploring longer. In the project, blood vessels and body tissues are new environments that nobody has really been to. Although the environment design is not a direct representation of real world objects, most users still felt interested and looked around frequently after putting on the VR headset.

4. Custom designed 3D UIs
Educational VR experiences should be custom designed to fit embedded instructional contents, which means that their user interfaces and 3D interaction techniques all need to be highly optimized for specific learning experiences. In other words, an experience of learning physics particles in VR cannot be simply modified with biology contents and used for biology learning in VR. Designers of educational VR experiences need to think critically about user interfaces and interaction techniques that are best suitable for chosen learning scenarios. For the current project, all 3D UIs and interactions were specifically designed based on real-life and magic metaphors to support learning activities in the experience.

5. Storytelling and narratives
Storytelling is an old tradition through which humans share and learn information and has been in existence since ancient times. However, when integrated with new instructional tools, it still serves as a fairly effective approach to contribute to people’s understanding and support learning. Practices of using stories to convey abstract science concepts were implemented in many studies. Helstrand and Ott (1995) used a science fiction novel, The Time and Space of Uncle Albert, to teach theory of relativity in four classes and their results indicated that using
novels to teach scientific theories is an efficient way to help students acquire basic science concepts. Klassen(2009) proposes using historical science stories in science education and conducted a case study of using a documentary-movie based story to teach theory of radioactivity among college physics students. With his case study, he outlined a methodology for researching, writing, and the testing of door-opening, literary science stories that could be used in combination with other forms of classroom instructions. Storytelling in VR is an emerging practice that is in its infancy currently. Although people are still experimenting with various approaches to make it right, it is for sure that the experience of being in a story in VR is much more engaging than watching a story on traditional screens. Educational VR experience design can also take advantage of current practices in VR storytelling and add fun and engagement to a user’s learning experience.

6. Guided experience
Although a lot of VR experience allows the users to self-explore the environment freely, a guided and scaffolded experience can be more beneficial in an educational context. J.J. Goo et al. (2006) investigated the effects of guided and unguided style VR learning on user attention and retained knowledge. Their findings indicated that the unguided task followed by the guided task made a considerable learning effect by giving a preview to the user and the guided task was more effective on teaching the focused learning contents. G. Singh et. al (2014) designed a mobile augmented reality system to scaffold historical inquiry learning and their findings from a case study suggested that after using the system, students demonstrated a greater understanding of inquiry and gained significant insight into the hidden history of the Christiansburg Institute (a historic site chosen for the study). In the project, a virtual guide was created to direct the user in the experience by providing necessary information from embedded
concepts and giving instructions on task performance. Therefore, the user will have a clear idea about what information to acquire from the environment and how to use it to complete assigned tasks.
Conclusion and Future Work

5.1 Conclusion

With this eight-month project, I was able to design and implement a working prototype of an educational VR experience that helps college freshmen learn specific immunology concepts. The project brought me a great learning experience from many aspects. First and foremost, I was able to add to my skill set with a beginner level programming capability in Unity game engine with C#, which allows me to go further with interaction design in future. Although there were frustrations sometimes during my learning process, learning programming without a computer science background didn’t look so intimidating to me anymore. And I felt more confident to continue learning and bring my C# programming skills to the next level in future. Apart from learning programming, I have also learned a lot from VR design experts about 3D UI and interaction designs and how to evaluate their user experience, adding another skill set to my previous UX/UI design experience.

This project wouldn’t have been possible without an interdisciplinary collaboration with people from various areas. Such an interdisciplinary collaboration experience has greatly added to my design dimensions and broadened my perspectives on design in a much larger scope. I have learned how to take advantages of my own knowledge and skills and connect them with subject matters from other areas and create something better than designing within my own field. To me, the power of interdisciplinary projects is that there are so many possibilities and directions you can take at the intersections of different areas and therefore generating much more room for creativity to happen.

This project also gave me a great opportunity to explore how to design a VR experience for learning, which is the first step to enter the area of educational VR experience design and research and connects
closely with my PhD research topic. There are many takeaways and lessons I've learned from the design process of this project and there are no better ways to experience them in person. My initial research in the area of educational VR design helped me understand some design principles and guidelines applicable to the application design in the area and established a foundation where I can explore further in the future and build upon my own findings.

5.2 Future Work

Based on the current working prototype created in the project, there are several future plans centered around it. First, the current project prototype is based on a high-end VR system and a desktop computer. Although it provides a highly interactive experience, the whole system is expensive with poor mobility and only accommodate one user at a time. In order to make the experience accessible to more students in a classroom, especially those at disadvantaged schools, a mobile version of the experience is set on schedule. With a mobile version, students can view the whole experience with moderate interactions in an affordable VR headset like Google Cardboard or Daydream.

Secondly, more user experience studies are needed to further evaluate the educational value of the project. High school teachers and students will soon be invited to try a project demo and their feedback will be collected and used to further improve the experience.

Lastly, the ultimate goal of this project is to use it as a testbed to investigate various aspects of a science learning experience within a fully immersive virtual environment. Research questions and hypotheses will be generated from the designs of current project. For example, how does the level of interactivity affect learning outcomes in an educational VR experience?
References


Appendix

A. Full VR Experience Recording
https://www.youtube.com/watch?v=UUezOAuKqNl

B. Full Scenario
At the beginning of the demo, a project PI and designer helps the user put on an Oculus headset and handles Oculus touch controllers to him and prepares him for a VR experience. After the user signals the PI that he is ready, the PI starts the demo on his laptop. The user immediately drops into the scene and finds himself inside a blood vessel in human body and around him are cells in different shapes, sizes, and colors. Some are floating and some are attached to the wall of blood vessel. The user turns around and tries to familiarize himself with the VE by looking up and down and venturing his steps back and forward. An invisible virtual guide, Lexie, starts her narration in the user’s earphone and instructs the user how to use controllers and contextual menus in the scene to navigate, select, and get necessary information for his actions. She will provide guidance and task assignments throughout the user’s VR experience. The user is told that in the demo he will be taking the role of a certain type of white blood cell (neutrophil) in human immune system in a fully synthetic immersive virtual environment that resembles a microworld inside human body, somewhere in a blood vessel and somewhere in body tissues. The user will stay inside a cockpit within a neutrophil body and control it to fulfill its responsibilities in the VE to protect human body from pathogen invasions. Since the neutrophil is the first responder in human immune system, it develops various ways to kill pathogens effectively based on different stimulations and chemical information (chemoattractants) it receives from the body. In the demo, the user will get familiar with a transmigration process of the neutrophils that allows them to migrate to sites of infection in a short time and employ their major killing mechanisms to fight pathogens. The user will need to decide which killing mechanism is the most effective under certain situations and selectively use it. Information of neutrophils, pathogens, and other types of body cells will be accessed via interactions with them in the VE, in various forms like text, audio, imagery, and animation.

Once Lexie walks the user through introduction and system navigation, the user continues to the main part of the demo by confirming on a dialog box that he understands everything and feels comfortable to begin his microscopic journey.

The user is inside an inactivated neutrophil now and moving with it in the blood vessel following blood flows. There are many other types of cells around the user and he uses his controllers to point to a cell of interest and retrieve its informa-
tion from displays in his cockpit. The user reads the information and moves to the next cell of interest.

He soon notices that there are a lot of particle-like small objects appearing on the surface of inner wall of the blood vessel and they are glowing on and off indicating they are interactive and may have some information to display. The user selects one of them and text information pops up. Lexie’s voice starts and tells him that these objects are chemokines generated by endothelial cells at the inner wall of the blood vessel and they pass information from a newly infected location in body tissues and carry pathogen information of the infection. Those chemokines activate patrolling neutrophils in the blood vessel and recruit them to site of infection.

Lexie continues to tell the user that his first mission in the demo is to control an activated neutrophil and migrate to the infection site ASAP to help other immune cells eliminate pathogens and protect his host. This is a timed mission, meaning that if the user’s actions can not increase his host’s health index to a certain level within a time limit, the host will die and the mission will fail. The user takes a glance at the right end display in his cockpit and notices that his host’s health index value is very low and infection value is pretty high at the moment. He must take actions to change the situation. The user soon feels his virtual movement with blood flows is slowed down and sees there are a lot of small tentacle like objects rising up from the surface of endothelial cells, grabbing his neutrophil body, and dragging it to the surface of endothelial cells. Lexie tells him that those tentacle like objects are selectins produced by endothelial cells and their main function is to tether and slow down neutrophils in blood flows. Once a neutrophil is tethered to the surface of endothelial cells, it starts to sense strength of chemokines and crawls to that direction with its pseudopods till it finds a location where it feels the strongest chemokine information and then passes through a gap between endothelial cells and finally migrates (extravasate) into body tissues. Once inside the body tissue, the neutrophil continues to follow the same gradient of chemokines from the site of infection and move there. Lexie indicates the user to look at a small round display panel under main displays in his cockpit and tells him that it can help him detect the strength of chemokine gradient from the site of infection and lead him there. The user looks at his chemokine sensor and finds as he moves forward, the sensor display turns to more saturated red color gradually, indicating he is getting closer to the chemokine gradient. The user stops when he sees his sensor display turns full red and flashes, telling him it’s time to look for an opening to start migration. He soon locates an opening at his left and “crawls” to it. As he reaches the edge of the gap, it is highlighted, indicating that the opening is activated and user can pass through it into
body tissues.

The user moves further into the gap and the screen darkens suddenly and after several seconds, it brightens again, meaning the process of migration into the body tissues has completed. The user finds himself floating in the space of body tissues and the environment looks different from that in the blood vessel. Lexie’s voice starts and asks the user to follow the chemokine gradients in his views to the site of infection. The user moves in the space within the body tissues while keeps an eye on the strength changes in his chemokine sensor. He soon finds a direction to which chemokine gradients are getting stronger and stronger as he moves towards it and decides that direction may lead him to the site of infection. The user moves along the chemokine gradients and soon sees more and more neutrophils and other white blood cells, like macrophages and monocytes, among them are some other objects in sausage-like shapes. He points to those “sausages” and finds out they are bacteria he needs to kill! But how?

The user selects one bacteria in his view and looks at his cockpit display for information. Several weapon options pops up in the display and provides him with information about their features. In general, the user can kill a pathogen in three ways: a. Phagocytosis: directly ingest small size pathogens with a minimum damage to host’s body tissues; b. Degranulation: release body granules containing antimicrobial proteins to kill pathogens with a medium level of damage to host’s body tissues; c. NETs (Neutrophil Extracellular Traps): release body DNA in a web-like structure to physically trap and kill large size pathogens with the greatest level of damage to host’s body tissues. The user needs to make a decision as to choose a most effective way of killing the pathogens without incur much damage to the body tissues.

Phagocytosis. The user looks around and spots a bacteria nearby in smaller size than others and decides to try weapon a. Phagocytosis to ingest the pathogen directly. So he selects the target pathogen directly in the view and it is highlighted immediately, an action UI pops up besides the pathogen and shows weapon options. The user chooses phagocytosis and he feels his neutrophil body moves to that bacteria and just as they are about to collide, the bacteria disappears. The user is then notified that the bacteria has been ingested and is inside his neutrophil body. A text box pops up and asks the user if he wants to watch the process of phagocytosis. The user thinks that it is interesting and confirms with yes. Screen darkens and then brightens with an animation of neutrophil engulfing the bacteria and breaking it down into pieces inside its body, audio narrative accompanied. After the animation is over, the user is directed back to his scene and Lexie’s voice comes up, telling the user that his lifespan as a neutrophil is
pretty short and his current neutrophil body is dying and will soon be cleaned by macrophages. In order to continue to kill bacteria and experiment with other killing mechanisms, he can select another neutrophil in the scene and move into its body for a new embodiment. The user notices a time countdown appears in his scene and he needs to move out of current body ASAP! He looks around in searching for a potential new body and there it is! He finds a wandering neutrophil in near distance and selects it immediately and a contextual menu pops up by the neutrophil, asking if the user wants to embody it. The user confirms with yes and the screen darkens, indicating the embodiment is in process. Once the screen brightens again within seconds, the user finds him already in the new body and a timer in the screen shows him that his new life is 7 hours long, which is within the average lifespan of a neutrophil (5-8 hours).

NETs. With a second life, the user decides to kill more pathogens and bring the host’s health index back to normal. He looks around and a very large size pathogen nearby attracts his attention and he decides to tackle that badass immediately like a video game boss. He selects and highlights the pathogen and chooses weapon c. NETs (Neutrophil Extracellular Traps). He then sees spider web like objects woven with many particles are shot from his body and cast on the pathogen. The NETs glows on and off on the pathogen till it turns gray and breaks into pieces, indicating that the pathogen has been killed. The user’s second neutrophil body is dying again with its launch of NETs killing mechanism, which consumes the neutrophil’s DNA substances and a lot of proteins. The user knows his time is running out soon and he has to look for a third neutrophil to embody.
C. Experience Audio Scripts

[ Virtual Guide Audio Scripts for Scene I. Transmigration ]

OPENING AND INTRO
Hi! Welcome to the immunology VR experience: a story of neutrophils. My name is Lexie, and I'll be your virtual guide for this experience.

In this experience, you will ride inside a neutrophil, the most abundant type of white blood cell in the human immune system. As a soldier in our division, you'll control your neutrophil to help eliminate evil pathogens infecting the body of your human host.

You'll need to learn about your controllers before we begin. Your left controller will be used to move around the blood vessel after your neutrophil stops flowing with the blood; I'll tell you more about that when the time comes. Your right controller lets you point out other cells in the blood vessel to learn more about them. Just hold down the trigger and use the laser beam to select any cell you can see to retrieve its information. OK, let's start the experience! Please pull the trigger on your right controller and use the laser beam to hit START.

START OF SCENE I
[At the beginning of Scene I]
You are now neutrophil trooper N9885 and serve in a phagocyte division. Your current mission is to patrol in this blood vessel till you are called for the next mission.

While you are patrolling, please let me introduce you to some other members of the human immune system around you. You will all fight together to defend your host from a pathogen invasion.

Look up and to the left! That giant blue guy in front of you is a macrophage, and it serves in the same phagocyte division as you do. You can hold down the trigger of your right controller and direct the laser beam to it to get detailed information about it.

Look! Those red, flat, round guys floating around you are red blood cells. They deliver oxygen supply throughout the body via blood circulation. And those light blue, small, spiky guys among the red blood cells are platelets, which are first-aid helpers to stop bleeding of blood vessels in injury.
Look at the big purple guy on your left side! It is a Plasma B cell, a white blood cell from the adaptive immune system. It releases antibodies as its main weapon to neutralize pathogens.

Have you noticed the dark blue guy on your right? That’s a neutrophil trooper just like you. You guys are the most abundant white blood cells in the innate immune system, and you will see many more of them when you’re doing battle with pathogens. But neutrophils have a short life. Your LIFE TIMER on the right side of your display panel shows you how long this neutrophil has left. But don’t worry; you can transfer to a new neutrophil before this one dies.

START MISSION OF TRANSMIGRATION
[Upon collision with selectins]
Oh, you collided with something! Don’t worry, these selectins are trying to grab you and slow you down because an infection has occurred somewhere near here in your host’s body tissues. Once the selectins have stopped you, your mission is to find a portal to transmigrate yourself into the body tissues so that you can join the battle against the pathogens.

[When fully stopped]
OK! Now you can use your left controller’s touchpad to roll around and search for the portal. Rest your thumb at the top rim of the touchpad to move forward and at the bottom rim to move back. Placing your thumb on the left and right sides of the touchpad lets you turn. Give it a try!

Hurry! roll yourself and look for the portal! Your host’s health index is decreasing!

[While the player is using touchpad traveling in the blood vessel and looking for the portal]
Do you see the round blue gauge at the left end of your control panel? That’s your chemokine sensor. Chemokines are chemical signals coming from the infection site through the portal. The gauge tells you how far you are from the portal, and it will start beeping when you’re getting close. The closer you get to the portal, the faster it beeps.

[When the player finds the portal and moves within its proximity]
Great! You’ve found the portal! Please move onto it to start transmigration automatically.
[Virtual Guide Audio Scripts for Scene II. Killing Mechanisms]

Audio 1 Movement explanation

START OF SCENE II

[At the beginning of Scene II]
You have now transmigrated from the blood vessel into body tissues. You are at the site of the infection, surrounded by your enemies—an army of bacteria. Your current mission is to use your weapons to eliminate as many as you can and bring back your host’s health index to a safety level of 900 points.

Before you engage in battle, you need to learn how to move around in the tissue. Hold down your right controller trigger to shoot a string to a nearby object, just like Spiderman shooting out his spiderweb. Once the other end of the string attaches to the object, you will be dragged towards that object as long as you hold down the trigger. Go ahead and try it!

<delay several seconds>

[While the user is trying the new movement technique]
Please shoot the string towards a bacterium in your view and move toward it. You will stop automatically when it’s in range of your weapons.

<delay several seconds>
Audio 2 Degranulation

[Once the user stops in front of a bacterium]
Now use the right touchpad to rotate up and down and left and right so the bacterium is right in the center of your view.

<delay several seconds>
OK, let’s learn how to use the neutrophil’s weapons to kill bacteria. On your left is your weapon control panel with three buttons. Let's try the first weapon called degranulation; it shoots out antimicrobial protein particles to kill pathogens. Use your left controller to touch the top button and activate it. Use the right touchpad to adjust your aiming reticle if necessary. Now pull the trigger on your left controller. Did you see a lot of blue particles shooting towards the bacteria in front of you? If a bacterium is hit by the particles, it will turn gray and stop moving. Keep shooting—once a bacterium is totally killed, your host’s health index will increase.

<delay several seconds>
Audio 3 Phagocytosis A
Let’s move towards another bacterium so we can learn more about your weapons.

<delay several seconds>

[Once the user stops in front of a bacterium]

Now let’s try a second weapon called phagocytosis, which basically means ingestion of bacteria. Remember, a neutrophil is a type of phagocyte, a category of white blood cells that ingest harmful foreign particles, bacteria, and dead or dying cells. This weapon is suitable for small bacteria. OK, please touch the middle button on your weapon control panel and activate the phagocytosis weapon. Now use the trigger on your left controller to point to the bacterium in front of you.

Audio 4 Phagocytosis B

[Once the bacterium has been encapsulated]

See how the bacterium is trapped and encapsulated? Now your neutrophil is moving towards it and taking it in. Once the bacterium is inside, toxic enzyme particles gradually break it down into small pieces. Look down below you to see this process in action. Then go destroy some more bacteria!

Audio 5 NETS

[When the user attempts to use degranulation or phagocytosis on a giant bacterium without success]

Uh oh, this enemy is too big to be killed with degranulation or phagocytosis. You need a more powerful weapon to kill it! Your ultimate weapon is called Neutrophil Extracellular Traps, or NETS. NETS can be activated by touching the bottom button on your weapon control panel. But beware, this is a suicidal weapon that will cause your neutrophil body to die. So only use it as a last resort when you need to kill very large bacteria. Once you pull the left controller trigger, the neutrophil body will release its DNA and antimicrobial protein particles to trap and kill the bacteria in front of you. However, once DNA is released, you will only have 3 minutes to use the weapon, and you won’t be able to move around because the neutrophil body is dying.

<delay several seconds>

Audio 7 NETS_v2

[After the user were introduced to phagocytosis and didn’t use degranulation and phagocytosis on big bacteria after some time]

Your ultimate weapon is called Neutrophil Extracellular Traps, or NETS. NETS can be activated by touching the bottom button on your weapon control panel. But beware, this is a suicidal weapon that will cause your neutrophil body to die. So only use it as a last resort when you need to kill very large bacteria. Once
you pull the left controller trigger, the neutrophil body will release its DNA and antimicrobial protein particles to trap and kill the bacteria in front of you. However, once DNA is released, you will only have 3 (2) minutes to use the weapon, and you won’t be able to move around because the neutrophil body is dying.

Audio 6 Teleport warning

[AAfter the user releases NETS DNAs and there is 1 minute left]
Attention! Your neutrophil body will die in 1 minute and you need to abandon it as soon as possible. You have a one-time chance to teleport yourself to another neutrophil nearby and get five more minutes of extended life to complete your mission. Please use either of your controllers to touch the green teleport button to your left, and you will teleport to the nearest live neutrophil. Hurry!

Audio 7 Teleport completed

[AAfter the user successfully teleported]
Whew! You made it to another neutrophil body and have 5 minutes of extra life! Please continue to kill bacteria and increase your host’s health index. Your goal is to reach 900 points.

Audio 8 Mission accomplished

[The user has killed enough bacteria and the host's health index is above safety threshold of 900]
Congratulations! You have killed enough bacteria to control the infection and your host is in a safe and healthy condition. Your mission has been accomplished!

[Other transcripts]

[Ask user to kill 2 pathogens with degranulation in order to unlock phagocytosis]
Please kill two pathogens with degranulation and your second weapon will be unlocked and available

[kill two pathogens with phagocytosis and unlock NETS]
Please kill two pathogens with degranulation and your second weapon will be unlocked and available

[When host health index is below 200]
Warning, Your host health is in critical condition! Please kill more pathogens to bring it back to normal.
D. Neutrophil Ingestion Metaphor Interaction Design Sketches

Interaction Design
Neutrophil Ingestion Metaphor 1

STEP 1
A user uses a VR controller to shot a laser beam to select a bacteria at a close distance. Upon laser beam selection, a semi-transparent capsule appears and encloses the bacteria, showing it's been trapped.

STEP 2
While the user holds the controller trigger and keeps the bacteria selected, the encapsulated bacteria moves into the neutrophil body.

STEP 3
Once the bacteria is inside the neutrophil’s body, the user can release the controller's trigger and the encapsulated bacteria will automatically scale down and placed underneath cockpit floor, the ingesting process completes.
Interaction Design

Neutrophil Ingestion Metaphor 2

**STEP 1**
A user uses a VR controller to shot a laser beam to select a bacteria at a close distance. Upon laser beam selection, a pseudopod appears and extends out of neutrophil body toward the bacteria. The user can then release the controller selection and watch the pseudopod reaching the bacteria.

**STEP 2**
The pseudopod will collide with the bacteria once it reaches it and grab it automatically upon collision, then it retracts back with the bacteria to the neutrophil body.

**STEP 3**
Once the bacteria is inside the neutrophil's body, the pseudopod disappears. The bacteria will then be encapsulated and scaled down automatically and placed underneath cockpit floor. The ingesting process completes.
E. Feedback from 3D Interaction Group on Project Demos

Selected Project Feedback from 3D Interaction Group

- Sickness mitigation: short experience, slow movement, frame of reference (cockpit)
- What is the end of the experience?
- Organic look to the cockpit?
- How do you follow the chemokines? Follow lights or colors?
- Need a sound/visual effect for teleportation so you know it happened
- Let user always pitch and yaw with RIGHT touchpad, no matter what weapon is activated
- During spiderweb travel, also pitch the neutrophil towards the target