Enabling Immunology Learning in Virtual Reality through Storytelling and Interactivity

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Abstract. Immunology concepts typically taught at the college level involve both factual and process-based knowledge and present learning barriers to college students. Immunology knowledge can be difficult for students to visualize and relate to. To help students better understand specific immunology concepts and increase their learning motivation and engagement, we designed the Immunology virtual reality (VR) application. Immunology VR leverages the rich interactivity and immersion offered by virtual reality systems to create a highly interactive and narrative-driven immersive VR experience that takes students on an exciting journey inside the human body. In this paper, we describe the design of the Immunology VR experience, focusing on our use of an interactive digital storytelling approach to enable learning.

Keywords: Immersive Virtual Reality, Storytelling, Interactivity, Immunology, Learning, Education, Instructional Design.

1 Introduction

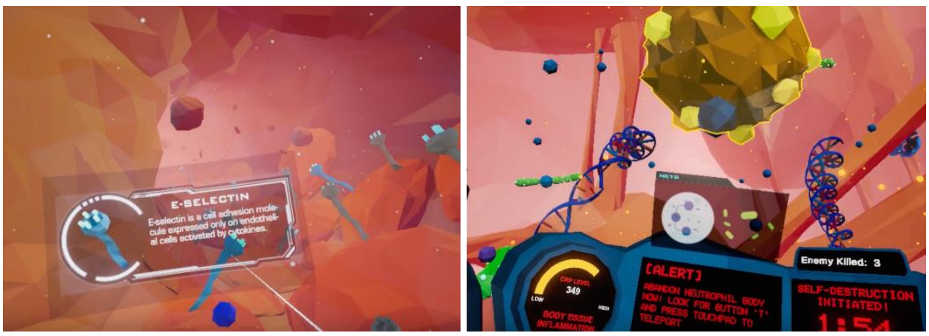

Fig. 1. Screenshots from the experience (left: selecting a virtual object to see its information, right: using the NETS weapon to kill bacteria in body tissues)

Immunology concepts typically taught at the college level are inherently complex, abstract, and process-based, involving difficult factual knowledge and jargon of the field (Raimondi, 2016) and presenting learning barriers to college students. Immunology knowledge can be difficult for students to visualize and relate to. Current methods of teaching immunology, usually in large-size didactic lecture classes plus lab exercises, do not promote learning in an active way for most students.

Research on STEM education has shown that to improve students' understanding of the concepts and increase their course performance, active learning is an effective teaching practice that supports learning (Freeman et al, 2014). Experiments that focus on different variations of active learning in biology and immunology education have shown that digital games (Cheng et al., 2014, Raimondi, 2016), card games (Su et al., 2014), and role playing (Elliott, 2010), are all effective instructional tools to improve students' learning of immunology concepts to some degree.

However, limitations of using games were also found in those studies. First, game designers and educators tried to embed all concepts into the game and let students learn the concepts completely from gameplay, which made the game simply a substitute for classroom lectures. Students felt frustrated with the complexity of the game and did not ultimately have fun playing it (Raimondi, 2016). Second, in a study of using card game for immunology learning, students were so absorbed in the competition of the game that they tended to neglect reviewing the embedded concepts and therefore learned little (Su et al., 2014). These limitations suggest that current game design for immunology learning doesn't do an optimal job helping students understand complex immunology concepts, even though they are more embraced by students than traditional lectures and show some effectiveness in promoting learning.

Emerging technologies provide new opportunities as instructional tools to promote active learning in STEM education. In particular, virtual reality (VR) has many strengths that can be used to create engaging learning experiences (Freina and Ott, 2015; Slater, 2016). Unique affordances of VR include rich interactivity, immersion, embodiment, multisensory stimuli, and a first-person point of view (POV). In the case of immunology learning, a VR experience could allow a learner to embody an immune cell with a first-person POV and travel inside the human body to hunt down invading bacteria, a scenario that would be difficult to visualize in other instructional media and tools. Existing studies on using VR for science education suggest that VR can help students learn abstract concepts with custom designed virtual environments (VEs) for learning (Dede, 1996). A meta-analysis on the effectiveness of VR-based instruction on learning outcomes also suggests that VR is effective for teaching students in both K12 and higher education settings (Merchant et al, 2014).

To make abstract science concepts accessible to students, many educators have been using storytelling techniques in instructional practices. Studies show that storytelling is an effective tool to communicate complex science concepts. In one study, researchers created short stories and used them in teaching science subjects like astronomy, biology, chemistry, geology, and physics. They found students had more accurate understanding of the subject concepts after reading relevant stories, as well as increased interest in the subjects (Clough, 2010). More recently, storytelling has been embedded into VR experiences by filmmakers to create a novel, immersive cinematic experience for general audiences (Dooley, 2017; Mateer, 2017), which brings a lot of new possibilities for instructional design.

In this paper, we present the design of a novel tool for college-level immunology learning, based on immersive interactive storytelling in VR. We hypothesize that this new tool, called Immunology VR (Fig. 1), has the following strengths:

- Rich interactivity provided by VR promotes active learning by doing and playing.
- Embedded storytelling and virtual guide features in the experience help learners work through complex immunology concepts and scaffold learning.
- First-person POV and immune cell embodiment create an immersive experience that engages students in contextual and situated learning.

2 Related Work

2.1 Definitions of Interactivity

Throughout the literature, definitions of interactivity vary from one to another due to different contexts and fields in which it has been used, and there is little agreement on a consistent definition (Sims, 1997; Domagk, 2010).

In the area of instructional multimedia, interactivity is considered an important characteristic of media and is believed to contribute greatly to learning (Sims, 1997). Barker (Barker, 1994) argues that interactivity is "a necessary and fundamental mechanism for knowledge acquisition and the development of both cognitive and physical skills." From a human-computer interface view, Sims (1997) defines interactivity as the function of input given to the user by the system and the action provided by the system in response to those inputs in a meaningful way. Researchers also attempted to identify levels of interactivity in instructional media design. One definition by Rhodes and Azbell (1985) proposes three levels of interactivity, ranging from the lowest level, reactive, where the learner has little control of content and structure; to coactive, where the learner is provided with controls for sequence, pace, and style; to proactive, the highest level, where the learner controls both structure and content. With this definition, level of interactivity is directly connected to the amount of user control over content and structure within the media.

In the context of VR applications, a widely cited definition of interactivity regards interactivity as the degree "to which users can participate in modifying the form and content of a mediated environment in real time" (Steuer, 1992). Roussou et al. (2007) specifies a three-level definition of interactivity in the context of VR learning based on an original definition by Pares (2001). It states that the interactivity in a virtual learning environment should promote the learner's physical and cognitive activities through one or more of the three forms: to explore the virtual environment by way of navigation (explorative), to manipulate virtual objects or elements (manipulative), and to construct or modify the environment as a whole (contributive).

Based on Steuer's definition of general VR interactivity and Roussou's definition of interactivity in a virtual learning environment setting, we identified types of interactivity that would be useful in our project by considering how interactive features of the VR experience could support the learning concepts through the user's actions. Specifically, interactivity provided by the virtual experience supports a user's freedom in navigation, the ability to select virtual objects and apply intended effects, and the ability to access specific learning information in the VE.

2.2 Interactivity and Learning

How does interactivity affect learning outcomes? Many studies have addressed that question in the context of instructional multimedia design. In an early study, Schaffer and Hannafin (1986) evaluated effectiveness of interactivity in a multimedia-based interactive video on learning. They compared the learning outcomes of 98 high schoolers with four treatment conditions with gradually increased interactivity levels in interactive video lessons. Their results conclude that students' learning recall was significantly affected by the amount and type of interactivity provided, and the most interactive version of the video lessons yielded the greatest recall. Khalifa and Lam (2002) investigated level of interactivity in web-based learning applications by comparing a distributed passive web-learning environment with a distributed interactive learning environment. Their results suggest that the interactive condition was superior to the passive condition in terms of both the learning process and learning outcome.

In the area of VR learning, there are fewer studies on the level of interactivity and its effect on learning. However, positive results were also found in a study by Bailenson et al. (2008), which examined the effect of interactivity on learning physical actions in VR. In the study, they found that the learners in an interactive VR condition perform better than those in a video learning condition.

To sum up, empirical evidence from past studies has shown that level of interactivity can sometimes be positively linked to learning outcomes.

2.3 Virtual Reality's Potential to Support Learning

VR has been embraced by educators and researchers as a powerful and promising tool for educational purposes because of its unique features that distinguish it from other instructional media (Mikropoulos and Natsis, 2011). Mikropoulos and Bellou (2006) list some VR features that pedagogically support learning, including creation of 3D spatial representations, multisensory channels for user interaction, immersion, and intuitive interaction through natural manipulations in real time.

Many studies have been conducted on the effectiveness of using VR for learning. A ten-year (1999-2009) review of empirical research on educational VR by Mikropoulos and Natsis (2011) indicates that the learning outcomes in almost all of the studies being reviewed (53 in total) are shown to be positive when mediated by educational virtual environments. In another study specifically addressing desktop-based VR technologies, Merchant et al. (2014) did a meta-analysis to examine instructional effectiveness of three major categories of desktop-based VR applications (games, simulations, and virtual worlds) on students' learning outcomes in K-12 and higher education settings. Their analysis suggests that games, simulations, and virtual worlds are effective in improving learning outcome gains, and that games show higher learning gains than simulations and virtual worlds.

Compared to research on desktop VR, there are fewer studies on effectiveness of immersive VR for learning. However, several studies conducted in immersive VR settings have also achieved some positive results. Kaufmann et al. (2000) built an immersive VR application, Construct3D, to support mathematics and geometry education. Their results indicate that the tool promotes learning by doing and training of spatial ability in its users and is useful to solve simple problems in mathematics and geometry education. Roussou et al. (2006) investigated the effects of interactivity in an immersive VR application, the virtual playground, on conceptual learning with primary school students. Their results suggest that immersive passive VR guided by a virtual robot works best in terms of student reflection, knowledge recall, and conceptual change. Dede et al. (1997) developed ScienceSpace, an immersive VR application to support learning of complex and abstract scientific concepts. Results show that students developed an in-depth understanding of the subject matter, and that students enjoyed the learning experience and appeared to be more engaged in activities. However, no significant difference was found in students' change of mental models with only a single session usage of the application.

It is noteworthy that development of many of these educational VR applications was driven by constructivist teaching and learning theory and followed a "learning by doing" approach (Dede et al., 1997; Kaufmann et al., 2000; Roussou et al., 2006) in accordance with the core principle of constructivism that knowledge is actively constructed through learners' interaction with the environment around them, and with other people in social and cultural settings (Sjøberg, 2007). However, our approach is to rely on storytelling as the main vehicle to convey necessary information to the learners. In doing so, we hypothesize that with interactive storytelling, new information will be more accessible to the learners, and it will be easier for them to process the information from stories than from self-exploration and discovery, given the complexity of the learning concept and the short exposure time in the VE.

2.4 Using storytelling for learning

Science is awesome to see but hard to explain. Science textbooks are mostly written with expository facts and are full of terminology, which creates learning barriers for many people. Thus, educators have used stories in science teaching to make subjects accessible to novice learners. Studies have shown that storytelling in science education promotes students' understanding of complex science concepts. Helstrand and Ott (1995) used a science fiction novel, The Time and Space of Uncle Albert, to teach the theory of relativity in four classes. Their results indicate that using novels to teach scientific theories is an efficient way to help students acquire basic science concepts. In another study, Banister and Ryan (2001) developed a science-teaching pedagogy using storytelling to help children develop science concepts about the water cycle. Their outcomes showed that, in the long run, the children remembered more abstract science concepts when taught with a storytelling-based pedagogy. Evidence from these studies suggests the possibility of using custom designed stories in immunology education to break down the complexity of abstract concepts and communicate them in an easy way to students.

The way a story is told and transmitted has also been influenced by rapidly changing technologies and evolving digital media. Digital storytelling is a recent form of creating interesting stories in combination with computers and multimedia such as computer graphics, audio, and video clips (Robin, 2008). Digital storytelling can also be interactive and custom designed for educational purposes. For example, RiverCity (Clarke, et al., 2006) is a research project that aims to train middle-school students in scientific inquiry skills in a multi-user virtual environment. The project is backed by a strong storyline in which a student travels back in time, bringing 21st century technology and skills to investigate and solve 19th century health problems in a small town. Results suggest that interactive storytelling in a multi-user virtual environment effectively encourages authentic scientific inquiry in middle school science education.

Storytelling in VR is not a new practice. However, studies that are specifically dedicated to the topic are scarce in the literature. One of the earliest examples of storytelling in VR was a Disney attraction based on the film “Aladdin” (Pausch, 1996). In the experience, the user follows a narrative storyline and flies a magic carpet through a virtual world. This project was an early VR storytelling attempt designed for a completely computer-generated virtual environment. After that, very few experiments with similar designs were found in the literature. However, in recent years, storytelling in VR, or cinematic VR, has been embraced by filmmakers in the form of 360-degree videos (Mateer, 2017). One example of such a VR storytelling experience is an award-winning animated music video, *Pearl*, in which the user acts as a ghost viewer who sits in the passenger seat of a 1970 hatchback and watches how a single father tries to raise his young daughter from a child to a teenager, and experiences joys and sorrows in life with them. Although storytelling in 360-degree video has the potential for teaching and learning, one major downside is that most of them lack the interactivity that supports the process of knowledge construction (e.g., allowing users to change viewpoints or interact with characters in the scene). We hypothesize that passive 360-degree video learning experiences might lead to a loss of engagement if a user is exposed to the medium very often or for a long time. Thus, we aim to provide immersive storytelling that is also highly interactive.

3 Designing Immunology VR

3.1 Design Approach

At the beginning of our design, we tried to define the scope of the virtual learning experience to be designed in terms of the amount of storytelling and the amount of interactivity. We developed the following major principles to be realized in the Immunology VR experience:

- The storytelling experience should be interactive, and learners should be able to influence the story by selecting among options.
- The virtual experience may include some gameplay elements (such as missions, goals, scores, and number of lives) to motivate learners to interact with virtual ob-

jects in the environment and to see a cause and effect relationship related to the embedded concepts.

- The experience should be guided so that learners can make better sense of the complex learning concepts embedded in a relatively short-duration experience.
- The tool should allow learners to make sense of new information through trial and error and provide necessary feedback to the learners' actions.

With these principles in place, we wanted to achieve a balance between storytelling and interactivity in our designs in terms of the influences they may have on concept learning. On the one hand, we did not want to create a passive storytelling experience in VR like many 360-degree videos. On the other hand, we did not want to make the experience as highly interactive as a computer game, since pure games may reduce learners' attention to the embedded learning concepts. Therefore, our design solution can be described as an immersive learning experience built on non-linear digital storytelling and gameplay connected through unique affordances in VR.

3.2 Design Process

VR experience design by its nature requires interdisciplinary teamwork, and our project is no exception. The project team includes members and expert advisors from different domains, including art and design, computer science, biological sciences, instructional design, education, and cinema. Within an interdisciplinary design context, there are no standard design processes for us to follow, so we had to explore and experiment with a design process that worked best with our design goals. We decided to focus our design process on providing an engaging and immersive user experience intended to help users learn immunology concepts. We chose an iterative human-centered design (HCD) approach to meet these goals.

An iterative design process was important for us, because in VR design it is unlikely to get the experience right on the first attempt. Rather, we needed to test our designs with end users frequently, identify major issues that hinder the user experience, make quick changes, and then test the new designs again. VR user experience consultant Jason Jerald (2016) states that, "VR design must be iteratively created based off of continual redesign, prototyping, and feedback from real users," which suggests that the iterative design approach is critically important for VR applications. He also proposes an iterative design process, the define-make-learn cycle, that is applicable to many common VR applications (Jerald, 2014). In the define stage, designers attempt to get a clear picture of what to make and list requirements of design goals. The make stage includes anything needed to create the experience and the way to put them together. In the learn stage, designers find out what works and what does not, and the answers are fed back into the define stage to help refine the design. Such an iterative design cycle was repeated several times during the ideation, prototyping, and implementation process of our project.

Our particular design process for this VR experience included the following major stages, which we describe in detail in the sections below:

1. Get to know the problem by communicating with an immunology professor and her students to identify learning barriers and determine learning goals
2. Based on chosen immunology concepts, create a story-based user scenario
3. Create visualizations of learning concepts and the user scenario
4. Design 3D interactions that help users carry out learning tasks in the experience
5. Create interactive experience prototypes in VR
6. Test the prototype with immunology students and make necessary refinements

3.3 Immunology Concept

We talked with professors and graduate students in the Biological Sciences Department to identify learning barriers in immunology education. From our conversations, we identified one specific concept area in immunology that many undergraduate students had problems with in regular classroom learning and lab exercises. The concept is about a specific type of white blood cells called neutrophils. Neutrophils are the most abundant white blood cells in the human immune system and serve as the first responders to any infections in the human body. Their major functions in the immune defense process involve fast transmigration from blood vessels to an infection site in body tissue and the use of several different mechanisms (degranulation, phagocytosis, and neutrophil extracellular traps) to kill bacteria there.

This learning concept involves factual, conceptual, and process-based knowledge and presents learning difficulties to students in classroom instruction. Specifically, students need to learn a complex process with many steps to understand the actions of neutrophils. In addition, our interviews with students suggested that extensive and unfamiliar terminology is another issue preventing them from fully understanding the concept. Finally, limited images in textbooks do little to help them understand and contextualize the ways that neutrophils work.

Based on the concept, we developed the following learning objectives for the VR experience:

- Students need to understand the role of neutrophils in the human immune system and how they complement other white blood cells.
- Students need to understand the steps and process of neutrophil transmigration, including selectin binding and neutrophil rolling.
- Students need to understand the differences between three major mechanisms used by neutrophils to kill bacteria: degranulation, phagocytosis, and neutrophil extracellular traps (NETS).

3.4 VR Story Design

After deciding on the immunology concept to be embedded into the virtual learning experience, we went further to create a story-based user scenario with specifications of user tasks and missions to be performed in the experience.

In the experience, the user/learner plays the role of a neutrophil "pilot" in the innate immune system's "armed forces" in the human body. The user's routine mission is to patrol inside the blood vessel and to be on call for infection alerts from the immune system headquarters. The user's mission starts when he is told that there is a serious infection happening inside his host's body tissues and he has limited time to go to the site of infection to prevent it from getting worse. However, the user first needs to look for a portal so that he can transmigrate into the infected body tissue. After finding the portal and transmigrating, the user is faced with different types of bacteria and needs to use his weapons to eliminate them. He needs to choose the right weapons for each bacterium in order to control both inflammation and infection.

The experience includes two scenes and follows a common three-act narrative structure. In the first scene, the user travels in the blood vessel and gets the infection alert, which starts Act 1 as an inciting incident. In the second scene, the user is faced with different bacteria and needs to find a way to eliminate them within a limited time. However, he is frustrated to find that his weapons are not all available initially, and he needs kill enough bacteria in order to use the weapon he desires. This is Act 2, where the main character is unable to solve the problem initially due to lack of skills and power. The user finally is able to access each weapon and figures out how to utilize their killing power to control the infection. This completes Act 3, in which the main character is able to find a resolution to the problem. However, in order to make the story interactive, the experience doesn't always conclude with a happy ending. The actual ending of the story, as in a video game, depends on the user's choice of weapons, the types of bacteria targeted by the chosen weapons, and the activation of a second life. The failure or success of the mission is ultimately up to the user and depends on rapid learning of the concepts.

3.5 Visual Design

3.5.1 2D Conceptual Illustrations

We started the visual designs of the experience with 2D conceptual sketches and illustrations and created several versions of storyboards. In the 2D visual design process, we were able to visualize key interactions the learners need to perform during the experience and get an idea of the complexity of 3D environment we were going to create in the next step. Fig.2 shows a storyboard that visualizes a neutrophil's transmigration process.

3.5.2 3D Asset Creation

The 3D asset creation was based on 2D conceptual sketches, illustrations, and many microbiology image references provided by immunology experts. We chose a low-polygon style instead of a photorealistic style for the 3D environment, immune cells, and bacteria due to several considerations. First, low-poly 3D models take less time to create, so they shorten prototyping time. Second, low-poly geometries do not need a complex texture and shader setup in a game engine like Unity3D, thus consuming less computing power and ensuring a high frame rate in VR. Third, the low-poly graphic style is popular in many mainstream games and will look familiar to learners.

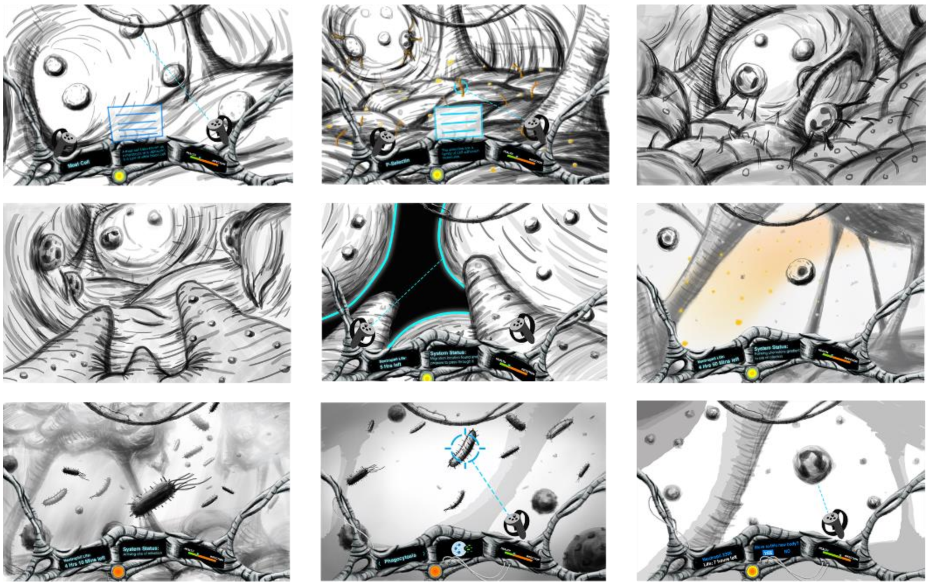

Fig. 2. Storyboard illustrating a neutrophil transmigrating from a blood vessel into body tissues.

For the creation process, we used multiple 3D authoring tools in our modeling pipeline by utilizing different features of each tool for our needs. For example, we used a 3D sculpting tool, Zbrush from Pixologic, to speed sculpt a rough shape of a 3D asset and imported it into Maxon Cinema4D to reduce its polygon count and create a stylized low-poly look. We then imported the low-poly model into Autodesk Maya to create custom animations for the model and export it into the Unity3D game engine. Fig. 3 shows the details of the 3D asset design workflow.

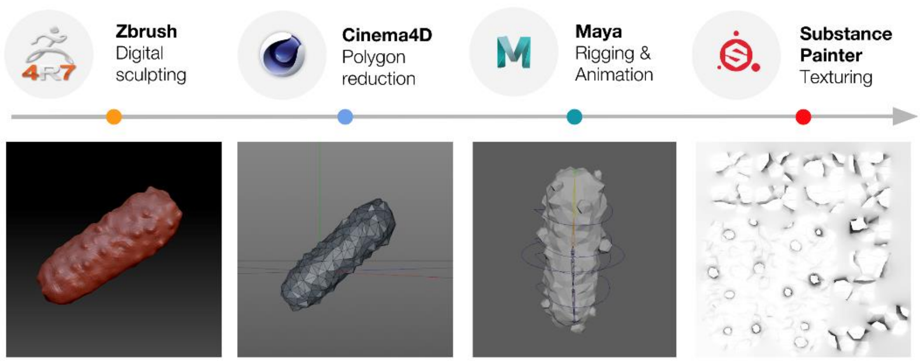

Fig. 3. 3D design pipeline and 3D authoring tools used for the creation of a bacterium 3D model in a low polygon style

3.6 3D Interaction and UI Design

3D interactions are a key component of our VR experience design. To create a smooth and intuitive 3D interaction experience in VR that helps facilitate the learning process, we adopted design strategies based on findings from previous studies on 3D interaction design. Laviola et al. (2017) suggest several strategies for designing and developing 3D interactions:

1. Borrowing from the real world. This strategy simulates and adapts interactions from the real world. Its major advantage is that users are already familiar with real-world interactions, reducing learning time.
2. Adapting from 2D user interfaces. This design strategy is based on the fact that most users are quite familiar with 2D UIs in their life through interactions with smartphones and computers. In addition, 2D UIs are much easier to use than 3D UIs for some 3D interaction tasks.
3. Magic and aesthetics. This strategy utilizes magic interaction techniques that overcome many human limitations in the real world and enhance users' capabilities to interact with virtual objects in the VE.

We developed our 3D UIs with references to real-world metaphors and magic interactions from popular culture such as adventure and sci-fi movies. We describe some design examples in Table 1.

Table 1. 3D interaction and UI design metaphors used in the experience

Interactions and 3D UIs in the Virtual Experience	**Metaphors from Real World**	**Metaphors from Magic UIs in Adventure and Sci-fi Movies**	**Reason to Choose the Metaphor**
Neutrophil control center where the user resides	Airplane cockpit		Users are familiar with dashboards and screens in real-life. The cockpit also provides a visual reference to the user in virtual movement and helps reduce motion sickness
Neutrophil rolling movement on the surface of blood vessel		Gyrosphere vehicle from *Jurassic World*	To provide a visual reference to the rolling movement when side structures of the gyrosphere rotate and help reduce motion sickness
Openings between endothelial cells in		A portal for transmission of people	Users are familiar with portals and

the blood vessels for the neutrophil to pass through and transmigrate into the body tissues		or objects in many sci-fi movies	their function in sci-fi movies
Neutrophil movement in the body tissues		A “Spiderman-inspired” movement that allows the user to shoot a string to a destination object and be dragged to it.	Users are familiar with how Spiderman moves in movies and the movement metaphor also adds novelty to the experience
Neutrophil uses different killing mechanisms to kill bacteria	A weapon control panel with buttons for weapon activation and allows the user to switch weapon among them.		Users are familiar with pushing a button to select an option in many digital devices in the real world

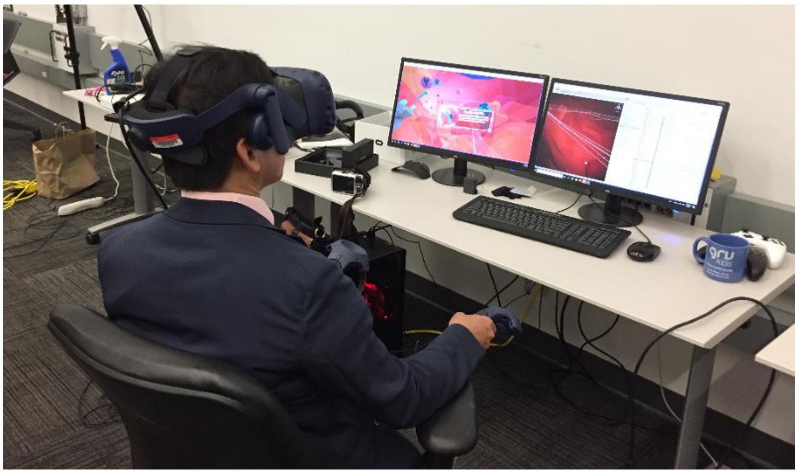

Fig. 4. A user playing the project prototype with an HTC Vive Pro VR system.

3.7 VR implementation

The VR experience was designed and developed to be used with an HTC Vive Pro VR system, which includes a headset, two controllers, two lighthouse trackers, and a high-end desktop computer to run the application. We chose the Vive system due to its higher headset resolution for sharper graphics, easily available development tools, and better headset ergonomic design that allows users with glasses to use it comfortably. Although the Vive system provides room-scale tracking, we designed our virtual experience as a seated experience with slow virtual movement, which fits best into our design scenario of a user piloting a neutrophil and moving inside the human body. We developed the application in the Unity3D game engine, a game engine that is popular among VR/AR game developers because of its simple development pipeline and abundant online development resources. Fig. 4 shows an image of system implementation with a user in the experience.

3.8 Design Iterations

An iterative design cycle was a major part of our VR experience design, which allowed us to continuously refine our user experience based on user test feedback. We share some examples of our iterative design practice in this section.

Our first example of iterative design was during the development of the story-based user scenario. We originally wrote the script to focus primarily on documentation and visualization of user interactions with the system, instead of telling a story involving the user. The scenario was also short of some key elements of a story, such as development of the conflicts and rising tensions that could help engage users. Having discovered the problem, we reworked the scenario with an addition of a virtual guide, Lexie, who talks to the user, gives instructions, and helps the story progress.

Fig. 5. Old and new weapon switching designs. (Left: using a virtual controller to touch virtual buttons. Right: presssing controller touchpad repeatedly to toggle among virtual buttons)

A second design iteration example relates to a usability design issue for the weapon switching mechanism. We originally used a button push metaphor in which users had to physically move their controllers in space to touch virtual buttons on the console. However, our user tests revealed that some users were confused about the relationship between virtual buttons and the physical buttons on the VR controller, because both were used in the experience. Our redesign of the weapon switching mechanism improved consistency by using the touchpad on the controller to toggle through the available weapons. Our user retest results showed that the new interaction design is more intuitive to the users and works much better than the original design. Fig. 5 shows a comparison between the two designs.

A third design iteration was about modification of the gameplay elements in the experience. Originally, the condition for success was to kill enough bacteria within a limited time to control the infection, which encouraged users to use the most powerful weapons frequently. However, our immunologist collaborators noted that neutrophils' excessive use of certain weapons will increase body tissue inflammation and worsen the situation, and that this concept should be taken into consideration in the design. So we refined the gameplay mechanism by providing body inflammation level information to users, and by defining the winning condition as a reduction of the infection while avoiding excessive inflammation. Fig. 6 shows the addition of an inflammation level gauge on the cockpit display panel.

Fig. 6. Inflammation concept on the dashboard display (top: old design, bottom: new design)

4 User Feedback

We have demonstrated and tested our working prototype of the VR storytelling experience with nearly 90 people from diverse backgrounds, including secondary school students (Fig. 7), science and art exhibition visitors, teachers and students from Biological Sciences, and visiting scholars of the University. Overall, we received very positive feedback from people who tried the experience. Specifically, in our user tests with 62 freshmen in Biological Sciences at Virginia Tech, we asked them how they felt about learning immunology in an interactive VR storytelling versus normal classroom learning. Many users felt that the experience was "fun," "interesting," "engaging," "interactive," and "helpful for learning immunology concepts." Nearly onefourth of the users mentioned (without prompting) that the experience made them "more focused" than they were in the classroom. Many users said that the visualization of a microscopic world inside the human body in the experience "connected the concept with visual representations" and "helped with learning." Some users also mentioned that the experience provided them with a "hands-on practice of immunology concepts through learning by doing" and worked better than lab exercises. Finally, several users indicated that the experience could serve as a good "add-on or supplement for classroom learning."

Fig. 7. Middle schoolers playing the Immunology VR experience.

5 Conclusions and Future Work

Motivated by existing instructional design tools and media in science education and emerging practices in VR storytelling, we proposed interactive VR storytelling as a novel instructional medium for immunology learning and have designed a working prototype of it. We explored a human-centered design process and discovered some design strategies that worked well in our design workflow. Our major takeaways from this interdisciplinary VR experience design practice can be summarized here:

- Communication is key
  It is very important to get to know the needs of the target audience thoroughly and create a VR experience specifically tailored to them. To achieve that, in our case, we communicated with our collaborators in Biological Sciences as often as possible in order to get the learning problems identified and learning goals correctly defined. We also frequently invited expert advisors from other fields to try the experience and give us feedback. Without effective communication between each party in the design team, we could not make things right in our designs.

- Iterative design pays off
  We have gone through several iterations during our design process, with changes made in storyline, learning concepts and gameplay mechanism integration, and 3D

UI usability. The result is a more smooth, engaging, and simple learning experience in VR. The time spent on those refinements and redesigns paid off.

- Co-design with learning concept providers is critical
  Since the developers on our team are not experts in immunology, we had to meet our collaborators in Biological Sciences frequently in order to make sure we visualized the concepts correctly. When in doubt, we provided them with several design solutions and asked for their preferences. With those practices, we were able to make sure that the learning messages conveyed from our VR experience truly respect the original concepts.

This working prototype of immunology VR storytelling will serve as a testbed for evaluating the validity of several research hypotheses in the future. Specifically, we hypothesize that the level of interactivity in a VR experience affects students' learning outcomes and are planning a study comparing three levels of interactivity. We are also interested in how different storytelling designs affect the students' learning experiences and will continue to develop different versions of Immunology VR for comparison.

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