A Study to Determine the Effectiveness of Augmented Reality to Increase Comprehension and Decrease Cognitive Load While Studying Protein Structure

by

Matthew Parrotta

A thesis submitted in partial fulfillment

of the requirements for the degree of

Master of Science (MSc) in Computational Science

The Faculty of Graduate Studies

Laurentian University

Sudbury, Ontario, Canada

© Matthew Parrotta, 2019

THESIS DEFENCE COMMITTEE/COMITÉ DE SOUTENANCE DE THÈSE
Laurentian Université/Université Laurentienne

Faculty of Graduate Studies/Faculté des études supérieures

Title of Thesis Titre de la thèse	A Study to Determine the Effectiveness of Augmented Reality to Increase Comprehension and Decrease Cognitive Load While Studying Protein Structure	
Name of Candidate Nom du candidat	Parrotta, Matthew	
Degree Diplôme	Master of Science	
Department/Program Département/Programme	Computational Sciences	Date of Defence Date de la soutenance April 17, 2019

APPROVED/APPROUVÉ

Thesis Examiners/Examinateurs de thèse:

Dr. Ratvinder Grewal
(Supervisor/Directeur de thèse)

Dr. Thomas Merritt
(Committee member/Membre du comité)

Dr. Kalpdrum Passi
(Committee member/Membre du comité)

Dr. Sabah Mohammed
(External Examiner/Examinateur externe)

Approved for the Faculty of Graduate Studies
Approuvé pour la Faculté des études supérieures
Dr. David Lesbarrères
Monsieur David Lesbarrères
Dean, Faculty of Graduate Studies
Doyen, Faculté des études supérieures

ACCESSIBILITY CLAUSE AND PERMISSION TO USE

I, **Matthew Parrotta**, hereby grant to Laurentian University and/or its agents the non-exclusive license to archive and make accessible my thesis, dissertation, or project report in whole or in part in all forms of media, now or for the duration of my copyright ownership. I retain all other ownership rights to the copyright of the thesis, dissertation or project report. I also reserve the right to use in future works (such as articles or books) all or part of this thesis, dissertation, or project report. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that this copy is being made available in this form by the authority of the copyright owner solely for the purpose of private study and research and may not be copied or reproduced except as permitted by the copyright laws without written authority from the copyright owner.

Abstract

Proteins are essential components of biochemistry, cellular biology, and medicine. Some students however may struggle with the representations of proteins found in the classroom. In this thesis , we present a novel augmented reality (AR) application that renders channel proteins and provides animations and lessons for students to learn from. This software was programmed using Unity C# scripting, as well as making use of open-source files from the protein database (RCSB PDB). The application was designed as a tool to help students learn about channel proteins structure and function. We recruited 30 undergraduate students for a study using the AR app and traditional methods. These students were then given a test on channel proteins, as well as a questionnaire on mental effort and enjoyment. The AR group did significantly better on their test scores, had lower cognitive load scores, and rated the experience more exciting than the non-AR group.

Keywords

Augmented Reality; Proteins; Protein Visualization; Education.

Acknowledgments

Firstly, I would like to thank my supervisor, Dr. Ratvindar Grewel, for allowing my research to reflect my interests, and encouraging exploration and discovery throughout the process of my Masters. His guidance and focus on literature and current research helped shape the direction of my thesis. I am grateful for his supervision.

I would also like to thank my committee member, Dr. Thomas Merritt, for his support and guidance through the process. Dr. Merritt provided invaluable insight during my research, as well as going above and beyond to help assist my research. I am thankful for the support he has given me.

Finally, I would like to thank my family for their support during my post-secondary education; my Mom, Dad and brother. I would also like to thank all of my friends for the encouragement. A special thank you to Emma Tomini.

Table of Contents

Abstract iv

Acknowledgments v

Table of Contents vi

List of Tables ix

List of Figures x

List of Appendices xi

1 Introduction 1

1.1 What is Augmented Reality 2

1.2 Mediums of AR 5

1.3 AR In the Classroom 6

1.4 Augmented Reality Versus Virtual Reality 8

1.5 Current Technology Used for STEM Students 10

2 Review of Literature on Pedagogy and Education 13

2.1 Types of Learning Processes 13

2.2 Typers of Learning Styles 15

3 Application and Experimental Design 19

3.1 Application Functionality 19

3.2 Chemical Visualization Techniques in AR 23

3.3 Differences to Existing Software 26

3.4 Lessons in AR 27

3.5 Developed AR Lesson Modules 28

3.6 Experimental Design 29

4 Results 34

4.1 Test-Scores Results 34

4.2 Effort Scores Results ... 35

4.3 Excitement Ratings Results ... 37

4.4 Power Analysis ... 38

4.5 Other Results ... 39

5 Discussion ... 41

5.1 Test-Scores Discussion ... 41

5.2 Effort-Scores Discussion ... 45

5.3 Excitement About the Lesson ... 46

5.4 Technical Comments About the Application ... 48

5.5 AR and Learning Styles ... 50

5.6 Limitations of the Study ... 51

6 Conclusion and Future Directions ... 54

6.1 Future Directions ... 54

6.2 Conclusion ... 55

References ... 57

Appendix A: Pre and Post Test Questionaire ... 63

Appendix B: Written Material on Channel Proteins ... 65

Appendix C: Channel Protein Quiz ... 67

Appendix D: Participant Consent Form ... 69

Consent Information Regarding the Study: ... 69

Investigator: Matthew Parrotta ... 69

Research Ethics Officer ... 70

Email ethics@laurentian.ca. ... 70

Date: ... 70

Appendix E: Participant Recruitment Letter/Classroom Recruitment Script ... 71

Appendix F: Laurentian Research Ethics Board Approval 72

List of Tables

Table 1 - Summary of the three types of mental processing that occur in education (Mayer, 2010) 14

Table 2 - Summary of the five styles of learning (Felder and Silverman, 1988) 16

Table 3– Summary of Ion Channel Categories 29

Table 4 – Summarized Results of ANOVA on Various Factors 40

Table 5– Summarized Results of T-Test on Various Factors 40

List of Figures

Figure 1 – Man using a VR headset. Photo Credit: European Space Agency (Permission to re-use via ESA, Creative Commons BY-SA 3.0 IGO)... 3

Figure 2 - Mixed Reality Continuum (Milgram et al., 1995). 4

Figure 3 - Pokemon Go being played in a field. A digital asset (Pokemon) is being rendered over the real world environment (Photo Credits: Andy Gstoll, thenextweb.com) 5

Figure 4 - Augmented Reality Protein Software in Use Visualizing a Nicotinic Acetylcholine Receptor. 21

Figure 5 - Representations of Adenosine-Triphosphate (Berg et al., 2002) 23

Figure 6 - Three Visualization Modes Offered in The Application (Left to Right: Ball and Stick, Back Bone, Space Filling View).. 25

Figure 7 – Floor Plan of the Testing Room 30

Figure 8 – Possible Distributions of calculated E-scores (Paas and Van Merriënboer, 1993) 32

Figure 9 – Distributions of E-scores after testing (AR is experimental; no AR is control).......... 37

Figure 10 - A potassium channel lined up so the purple potassium ion is in the channel portion of the protein 43

List of Appendices

Appendix A: Pre and Post Test Questionaire ....**Error! Bookmark not defined.**

Appendix B: Written Material on Channel Proteins..........**Error! Bookmark not defined.**

Appendix C: Channel Protein Quiz ....**Error! Bookmark not defined.**

Appendix D: Participant Consent Form............................**Error! Bookmark not defined.**

Appendix E: Participant Recruitment Letter/Classroom Recruitment Script............**Error! Bookmark not defined.**

Appendix F: Laurentian Research Ethics Board Approval**Error! Bookmark not defined.**

1 Introduction

Human computer interaction has evolved in recent years past the traditional notion of a desktop or laptop computer; computer technologies are embedded in everyday devices, and smartphones have exploded in popularity and processing power (StatCounter Global Stats, 2018). Computer interaction has shifted more and more towards using smartphones and specific apps, and in the recent past, smartphones have given rise to the opportunity to use augmented reality (AR) applications. The potential applications of AR software are diverse, but an area of interest is its use in education. AR allows the visualization of normally non-visible objects to be possible in 3D space, which is a potential benefit to many areas of study and education.

Fields that rely on conceptual models can often be strenuous and difficult for students to grasp and master (Johnstone, 1991; Millar, 1991); one such field is biochemistry. Although one can observe reactions with their eyes, or see cells through a microscope, molecules and macromolecules (proteins) can only be viewed structurally through electron microscopy (which is expensive and not feasible for educational purposes), so the burden is on the student to maintain a mental model of what is occurring on the atomic scale. Two-dimensional representations of molecules and proteins exist (images, paper models, etc), but do not easily allow abstraction in 3D, which is essential for understanding the mechanisms and functioning of these species. This cognitive burden can hinder the learning process and cause additional stressors in the classroom (Siti et al., 2016). AR has the potential to alleviate this burden, as visualization of these normally un-observable phenomenon can be achieved. In this paper, an investigation into the use of AR in the classroom is presented, as well as an introduction to a proprietary application that allows visualization of proteins using AR.

1.1 What is Augmented Reality

Augmented reality falls under the category of *mixed reality* applications (Milgram et al., 1995). AR is a type of reality that is superimposed over our real-world environments. It can be distinguished from virtual reality (VR) because it does not remove the individual using it from their local environment as VR does (Milgram et al, 1995). This distinction was made by Milgram and colleagues in the 1990's, before any VR or AR technology was commercially feasible. More contemporary literature still highlights that AR is a type of reality where digital models and assets are rendered over-top of our real-world environment, while VR is a completely computer generated environment foreign to our own (Yuen, Yaoyuneyong, and Johnson, 2011). In the figure below, you can note the man wearing the VR headset has no ability to see the "real-world"; his vision is completely obscured and encompassed by the VR headset.

Figure 1 – Man using a VR headset. Photo Credit: European Space Agency (Permission to re-use via ESA, Creative Commons BY-SA 3.0 IGO)

The individual in the photo uses two hand-held controllers that allow him to simulate his own hands in the VR application, which is pictured on the screen. The VR headset being used in this photograph is the HTC vive, which is a commercially marketed VR headset that has only been available in recent years.

We can compare AR to VR partially by observing the *reality-continuum* put forward by Milgram et al (1995):

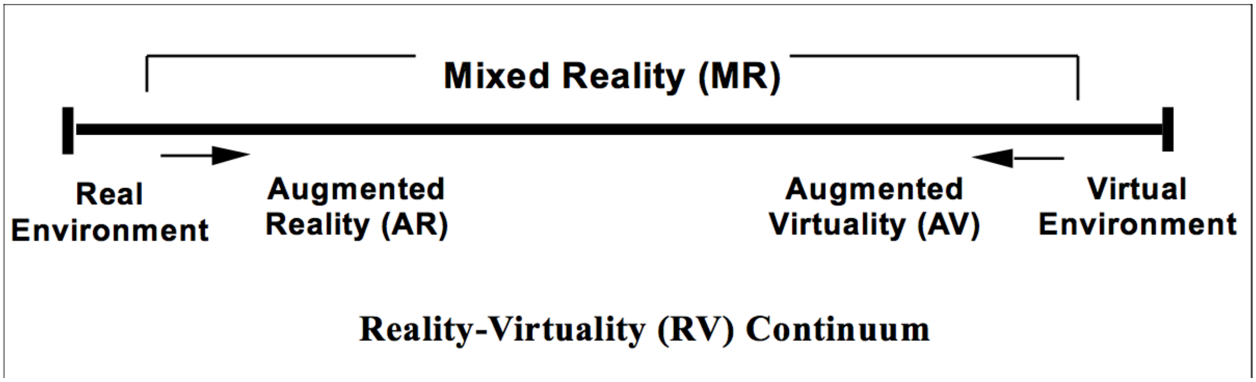

Figure 2 - Mixed Reality Continuum (Milgram et al., 1995).

Augmented reality is distinguished from VR not only by its placement on the reality continuum, (as we can note it is located on the left hand side, closer to the real environment) while VR (called Augmented Virtuality in figure 2) is located on the right hand side near a virtual [computer generated] environment. An example of how AR is more closely linked to the real environment is shown in the photo below:

Figure 3 - Pokemon Go being played in a field. A digital asset (Pokemon) is being rendered over the real world environment (Photo Credits: Andy Gstoll, thenextweb.com)

In the photograph above, the digitally rendered asset is placed in the real world environment, the soccer field. AR utilizes the cameras on smartphones and tablets to “see” the real world, and uses its processors and computer-vision algorithms to correctly place the asset in the real world. This type of reality is distinct from VR because the individual is not removed from their environment. In the example above, the individual is still present the soccer field, and rather than their vision be obscured with a headset, the AR comes from the assets seen through the smartphone.

1.2 Mediums of AR

AR applications are normally used on smartphones or tablets, utilizing these devices' camera and processing power. There are some head-mounted displays (HMD) available that attempt to utilize AR rather than VR, allowing the user to render digital models and assets without having to hold a tablet or phone. An example of these headsets is the Google Glass, a headset released in 2014 that was one of the first to introduce displays that overlay on top of the real world. The headset did not become rapidly adopted for AR use because of its technical limitations and large price. This is similar to other more contemporary HMD's, such as the Microsoft HoloLens, which although more sophisticated than Google Glass, failed to reach expectations that would allow it to be an alternative to smartphones and tablets for AR experiences. HMD's for AR are likely to become more widely adopted once the technology has advanced and the price point is able to be reduced.

1.3 AR In the Classroom

Technology in the classroom is not a new notion, but as the smartphone revolution continues, educators and curriculum developers should be focusing on how this emergent and ubiquitous technology can be implemented in education. According to the Pew Research Center, in 2015 73% of teenagers (this point need a geographic qualifier – correct?) own or have immediate access to a smartphone (Lenhart et al, 2015). More recent reports have that number up to 77% on average, with the age demographic of 18-29 year olds owning a smartphone with a rate of 94% (Pew Research Center, 2017). With adoption rates so high and the decreasing prices and increasing availability of powerful smartphones, integrating them into education is a step some have already begun to take. Küçük et al (2017) showed that the use of an augmented reality application significantly increased medical students test scores and decreased their cognitive load when learning anatomy . In the Küçük et al study, cognitive load was measured using the cognitive load scale, developed by Paas and Merriënboer (1993). The study displayed the effectiveness of integrating an AR application into the learning process, not only objectively through test scores, but when asked if the application helped them learn, 76% of those who used the AR application answered 'yes', with the remaining 24% answering 'partially'; no participants indicated it was detrimental to the learning process.

In recent years, other studies have been done focusing on the efficacy of AR for education. Tsai (2017) reviews several studies where AR is used to provide students a means of visualizing objects that normally could not be, or would otherwise be difficult to do so; one example includes an application to teach elementary school age students botany, allowing them to visualize leafs of native plants and non-native plants . The students that used AR teaching tools displayed a greater retention of the information when quizzed, and this highlights how AR can allow visualization of unobservable phenomena, in this instance, leaves of plants that are not native to the area (Tsai, 2017). A separate review paper by Saidin et al highlights how AR education can alleviate literacy and language barriers, as a well designed application could potentially need less text to teach, as the observational based model of learning is sufficient and does not require as much reading as traditional textbooks would (2015). A well designed application could also alleviate some of the cognitive load associated with maintaining a mental visualization of the topic being covered (Saidin et al., 2015). This mental processing is an important component of education, as disseminating information into pertinent and non-pertinent facts can be challenging for some students.

1.4 Augmented Reality Versus Virtual Reality

As augmented reality has become more and more accessible to the public, VR has had an increase in public interest, and along with decreasing costs for powerful enough VR-ready computers, the technology could have potential benefits in education. Multiple studies have been performed on the viability of VR in the classroom; Hussein and Nätterdal (2015) performed an analysis study on previous VR experiments. In their analysis, they demonstrate that some of the effectiveness of VR education comes from the novelty of the experience; many students have not had an opportunity to try virtual reality, and this is both a pro and con to the educational process. Students may become invigorated with the topic being studied, however they may be distracted or overwhelmed by the uniqueness of VR and it distracts from the learning process. Additionally, there were reports of motion sickness or other nausea caused by using the headset, a problem that persists with VR technology today in some people. A similar analysis performed by Merchant et al (2014) studied 29 previous VR experiments focused on educational games and simulation, with over 3000 total participants across studies. With such a large sample pool to study, Merchant et al concluded that games and simulations have a positive effect on learning depending on the context they are presented in and with which topic they are paired. However, Merchant et al also demonstrated that repeated exposure to VR applications for education lowers the achievements of the students, supporting the notion that one of VR's strengths is its novelty.

An early version of the application presented in this paper was created to work with the Oculus Rift, a VR headset, utilizing Unity, a scriptable game engine that can render 3D graphics and is compatible with the Rift. The design of the application shifted to augmented reality for several reasons. Firstly, the previous research discussed illustrating the novelty-dynamic of VR was recognized as a potential problem for VR in the classroom once the novelty has worn off. Secondly, the price and bulkiness of the VR headset deterred its use, and in long term educational applications, the cost would be substantial to equip a classroom with enough computers and headsets to allow a proper group learning experience to occur. These two factors placed a constraint on the current study, and forced us to evaluate different options for educational technology. AR was selected and the design of the application changed over for several reasons. As discussed previously, the adoption rate of smartphones is extremely large in younger people, so the price of the technology is offset by mass ownership. Additionally, most modern smartphones (2016 and onward) are capable of some level of augmented reality processing. Finally, several studies demonstrated the effectiveness of AR as a teaching tool (Joo-Nagata et al., 2017; Di Serio et al, 2013; Huwer and Seibert 2018) provided enough validity to continue with AR, and not VR, as the primary technology. A study by Cai et al (2017) used AR without smartphones, but rather using a Microsoft Kinect Camera, which allows detection of hand movements and gestures. Their study demonstrated an improvement in scores even without using smartphones as the primary technology facilitating the AR. With these previous studies in mind, we hypothesize that AR is an effective education tool regardless of the technology that runs it, and that it may provide similar positive learning experiences to those that VR could without the additional negative side effects and costs VR has associated with it.

One of the potential downsides to AR is distraction in the classroom. A recent study demonstrated that the mere presence of one's smartphone on the desk (although not being used) has a statistically significant effect on attention and memory (Ward et al., 2017). Another study by Lee et al (2017) demonstrated that receiving text messages during lectures can distract students, as well that the distraction from smartphones can affect the general population, and not just those that have a fear of being away from their smartphone (*Nomophobia*). Additionally, a study by Stothart et al (2015) demonstrated that the distraction after receiving a phone call or text message impedes performance for some amount of time, before attentional facilities are reorganized and focus returns fully to the task. These studies demonstrate one of the largest inherent problems with relying on smartphone technology in the classroom; the potential for distraction and the misuse of devices for social or personal matters. This negative should not completely negate the use of smartphones however, as the possible benefit from AR technologies is widespread and vast and these negative can be acknowledged and dealt with or mitigated. Curriculum developers and school boards will need to address problems with smartphone distraction on their own and implement solutions, rather than ignore the technology completely. Smartphones allow for extremely portable and adaptable educational software, that can cater to students learning styles and, in the right context, can blend seamlessly in to the classroom environment.

1.5 Current Technology Used for STEM Students

Currently in undergraduate education, technology is being utilized to further the education of students. In a 2018 study, it was reported that 30% of undergraduate students utilize video lessons in order to learn and study material (Rodriguez et al., 2018). Eaton and Shepard have found that although online teaching-modules and online based quizzes/problem sets are commonly used, they hold less value to students than problems taken directly from the textbook, and even less value to students than practical, hands on, “real life” applications of problems (2014). Modern STEM (Science Technology Engineering and Mathematics) lectures consist primarily of PowerPoints and slide show style lectures that rely on laboratories to reinforce the content; however, these labs can be held potentially weeks after the initial lesson is given. The usage of online modules, such as WebAssign (www.webassign.net) grows despite students’ preferences to real-world applications. This is unsurprising however, as schools, businesses, and society at large are moving towards the digital world.

Some fields in STEM have not adopted contemporary computer software yet and still rely on older models to teach. For example, it is not uncommon in a chemistry laboratory to see a ball-and-stick molecule kit. Models like this have persisted in education because they are effective, however they are expensive and parts are easily misplaced. Similarly, in biology labs, life size plastic models of organisms are still used for students to study, despite the fact that students have to physically go to the location of the models because they are too expensive to purchase themselves, as well as being large and cumbersome.

There are a select few AR and VR applications that are used in education, but because the technology is so novel, it has not yet been widely adopted. Several of these applications are also proprietary and not yet commercially available. One of the few commercially available AR application companies is ARLoon, who have a variety of STEM related AR software’s available on both iOS and Android devices (www.arloon.com). This software is marketed towards elementary and early high school students however; the niche for AR applications in post-secondary STEM students has not been filled.

2 Review of Literature on Pedagogy and Education

One of the major potential applications of AR technology is within the realm of education. Teaching and disseminating information effectively is a large field on its own. Numerous educators have described what makes a lesson effective, and how personal differences in students should be considered when deciding how to best present material. In this section, we will review the distinctions of learning styles and how that affects the presentation of educational material.

2.1 Types of Learning Processes

While learning and acquiring new knowledge, research indicates that there are certain neurological processes at work. A pedagogical review of types of mental processing done by Mayer can help define what components of education drain which cognitive resources; these are listed below in table 1 (Mayer, 2010):

Type of processing	**Description**
Extraneous Processing	Cognitive processing that occurs when the material or lesson aren't formatted to allow a flow of facts and concepts without interruption. An example is a written description of the structure of the heart on a textbook page, but the corresponding illustration is on another, wasting time and cognitive effort to flip between pages and maintain a working memory of the text and image

Essential Processing	These are the essential facts and concepts that cannot be stripped away from the material or lesson without losing the point. Essential processing is an unavoidable cognitive load which balances short term-working memory with the sensory stimulation to begin the integration process of knowledge. This cannot be removed from the learning process and its cognitive load is proportional to the complexity of the material
Generative Processing	This is supplementary to essential processing, and is a processing to "make sense" of the material learned from essential processing. Generative processing is a deeper understanding of the material, and the authors describe it as the cognitive processing most associated with integration and organization of the knowledge gained from essential processing. Generative processing is affected my motivation and interest, with the more subjective interest shown, the more generative processing that occurs.

Table 1 - Summary of the three types of mental processing that occur in education (Mayer, 2010)

Mayer's models of processing are relevant to understanding the differences in processing at different stages of learning. Essential processing for example, cannot be removed from education, so one must remain aware of the burden of the essential processing presented in their specific lesson. Depending on the subject matter, essential processing in and of itself can be a large cognitive burden on the learner, especially in STEM (science, technology, engineering, mathematics) fields, where essential information can be overwhelming to some students (Iossi, 2013). Educators and lessons should reflect the organizational paradigm presented by Mayer, in which one consciously plans what content is essential and *must* be presented, and what is extraneous and supplementary to the core content. Ideally these two processing types would be balanced in a way that reduces essential and extraneous processing, while increasing the generative processing that encourages students to make connections and inferences that help encode concepts to memory.

2.2 Typers of Learning Styles

One of the other challenges that faces educators in the STEM field is the need to present concepts from multiple perspectives (Treagust and Duit, 2008). Multiple perspectives and alternative approaches to concepts in STEM are essential for encouraging generative processing from students, as well as allowing a student population with multiple learning styles to all learn the concepts effectively. Felder and Silverman discuss the range of learning styles and preferences different students can have, and how these learning styles will affect how much they can learn from certain material (1988). These styles include:

Learning Style	**Description**
Sensing/Intuitive	Sensing learners like hands on, observational examples (like laboratory tutorials). Intuitive learners also like hands on examples, but are more logical and generally score higher on tests than primarily sensors. These learners should be taught with alternating *concrete* and *abstract* lessons (ie in class lessons then labs)
Visual/Auditory	Visual students remember visual content best (graphs, charts, photos, visual input) while auditory learners remember what they hear best. Silverman and Felder state that most college age students are visual learners, but lectures are

	sometimes primarily auditory. They recommend both auditory lecturing and visual information
Inductive/Deductive	Inductive learners draw inferences from observation and trials, while deductive learners learn from building up on previously known content, normally in a more theoretical classroom setting. Felder and Silverman suggest that students like this learn best when they are shown the phenomenon they will be studying (so they can observe in an inductive manner) and then are deductively proved what they saw in a conventional lesson
Active/Reflective	Active learners like to partake "actively" in the learning experience, and require hands on, immersive experiences to learn. Reflective learners however learn best in a setting where they are presented content, and then allowed to reflect on it passively and in their own time
Sequential/Global	Sequential learners are students who thrive when presented with a traditional curriculum, and are taught content in order of easy to hard, and then tested, to move onto the next topic. Global learners do not thrive in order-based learning, and rather have "I got it" moments in the learning process, where they understand completely; however, these moments may be between periods of no progress or understanding. Learners like this need to absorb all content "globally" and will eventually retain all content and understand how topics relate to one another globally

Table 2 - Summary of the five styles of learning (Felder and Silverman, 1988)

Table 2 highlights the unique learning styles outlined by Felder and Silverman (1988). A single student may present as any combination of the five learning styles; this complexity leads to problems for curriculum and lesson developers as they have to be able to present material so everyone can approach it, however the number of combinations of learning styles and lesson preferences can make this challenging. In addition to each students' unique learning style, the 'students essential, extraneous, and generative processing will differ as a function of their learning style. This additional level of complexity compounds the challenge of creating universally applicable lessons for diverse student groups (Felder and Brent, 2005). Despite this, some research indicates that even if a lesson is focused on catering to the needs of spatial learners (for example), the lesson will not only be of benefit to them, but may not significantly increase cognitive load and processing for non spatial students. Research demonstrates that although 3D modelling software is of benefit to those with a greater sense of spatial awareness in regards to test scores and cognitive load, it does not negatively impact those who have a lower spatial sense than others (Huk, 2006).

AR applications can help to alleviate the pressures of unique learning styles and information processing techniques. Augmented reality applications allow for visualization of concepts that are normally difficult to conceptualize, effectively decreasing the amount of essential processing required for the student to maintain a constant mental model of the lesson in question. AR can similarly decrease extraneous processing, as all the information needed for a lesson could be housed inside of an application. The technology can be applied to several learner styles as well, with the hands on, observational, nature of AR appealing to visual, sensing, active, and inductive learners. These learners would benefit from the independent exploration and observation of 3D models, and the lack of constraint to a traditional chalkboard lesson. In addition to these possible benefits, research has shown that novelty of technology can have a positive effect in the learning process (Rossing et al., 2012).

3 Application and Experimental Design

An application was developed using Unity and Apples ARKit, the augmented reality engine supported by apple for there iOS devices. The application was scripted primarily using C#, with some JavaScript used in conjunction, all done within the unity engine. The application will construct a 3D protein model from a protein database (PDB) file, retrieved from the RSCB Protein Database (rcsb.org, The Protein Databank 2000). These files contain structural, and biochemical information pertaining to a specific protein, that was isolated and observed in order to create the PDB file. The protein database has documentation for over 140,000 proteins available to download, and the application works with most of the entries, as long as a standard PDB file is present. It is worth noting the database has other file formats that currently do not work with the applications 3D model builder, however exceptions for non standard documents can be implemented in a later version. The structural information from these files is used by the application to compute a 3D representation of the information.

3.1 Application Functionality

Once the application constructs a 3D model, it can be stored and mapped to a specific card-image, where a unique card image corresponds to a unique protein model. These images are then printed, and when the application's AR camera observes the protein-specific card, it renders the model above it, on the device screen – as if floating in air in front of the user. The models can be scaled, rotated and translated in 3D space once rendered, and the protein database allows for open-source use of any of their files (https://www.rcsb.org/pages/usage-policy). These actions are performed using touch screen actions, which are familiar and intuitive to most smart device users. In addition to rendering the protein and allowing its size and position to be changed, the application allows for protein-specific animations and lessons. When the application recognizes a card and renders its specific protein, it is able to set up animations specific to that protein, as well as allow a pop-up text box that can be used to disseminate information specific to that protein and its corresponding animations. The animations and lessons can be scripted using programming languages (as was done for the development of the application), but it can also be manually created using the unity engines drag and drop functionality.

The program was developed using Unity for a multitude of reasons. Firstly, Unity allows full scripting using conventional programing languages C# and JavaScript, so functions such as reading through the PDB files to create models could be done programmatically, as well as the construction on the 3D model using Unity assets can be done programmatically. Unity allows Unity-projects to be exported and compiled on various devices, including both iOS and Android executable applications. This ability is a benefit to the scope and scalability of the software, as the vast majority of phone and tablet owners are using an iOS or Android based system (StatCounter, 2018). One of the other benefits of Unity is future developers do not necessarily need to know how to script to develop new lessons for AR applications; Unity allows drag-and-drop interactivity to create animations and text prompts, so future educators who cannot program could use this functionality to design unique lessons for specific proteins.

An example of the final interface and a screenshot of the application in use is included below:

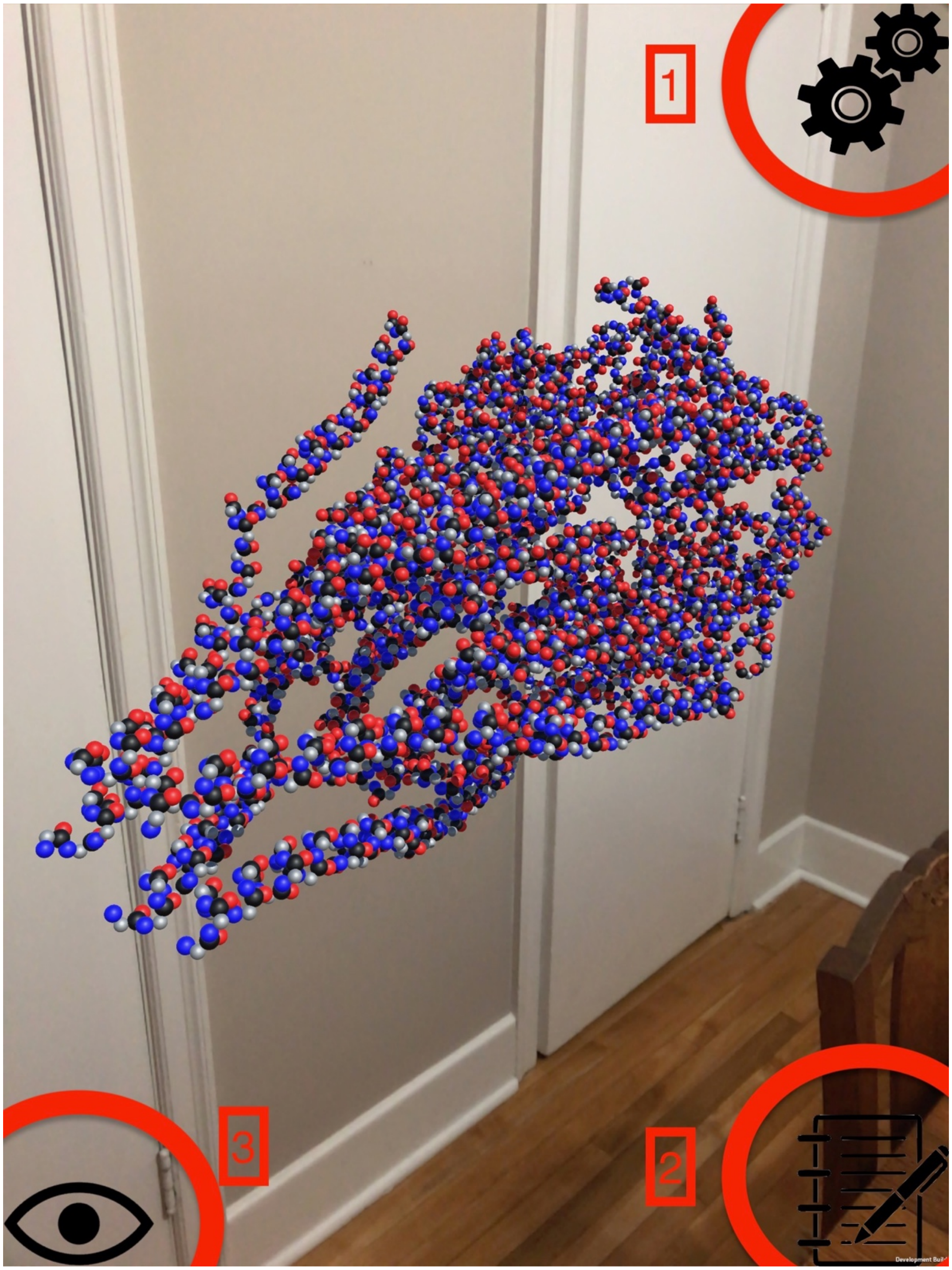

Figure 4 - Augmented Reality Protein Software in Use Visualizing a Nicotinic Acetylcholine Receptor.

In the above figure 4, a screenshot of the application in use was taken. The figure has three highlighted buttons. The button labeled 1 is the function button, which starts unique animations and lessons for each card programmed to have them. Button 2 is the lesson button, which when selected, displays a text pane with information regarding the protein. The 3rd button is the visualization button, which cycles through the three visualization options (described further below). The protein in this example is a large channel protein flipped onto its side using the rotate functionality of the application (users may use two fingers to pinch the size or rotate two fingers to rotate the model). The user is then free to move within the confines of their physical space and observe the structure from their desired position, as if the model is physically there.

There are certain limitations to rendering proteins using AR on a smartphone or tablet device. Proteins are large, complicated 3D macromolecules, and rendering all of the atoms and bonds involved is computationally expensive. Proteins range in size (defined by the length of its primary sequence) and small and medium sized proteins can be displayed by a phone without any slowdown or problems, however larger proteins exhibit this problem. One example of this is the PDB entry *2bg9*, which is the Nicotinic Acetylcholine Receptor (http://www.rcsb.org/structure/2BG9) . This protein has 1849 residues in its primary sequence, and a total of 14924 atoms to be rendered, not including bonds. Rendering this number of individual atoms is very taxing on the processor of the device. To combat this, certain visualization properties were considered for the application.

3.2 Chemical Visualization Techniques in AR

The application allows for three types of protein visualization, which the user is able to toggle through at their discretion. The three visualization modes are based off of conventional molecular representations found in chemistry, as displayed in figure 5 (Berg et al., 2002).

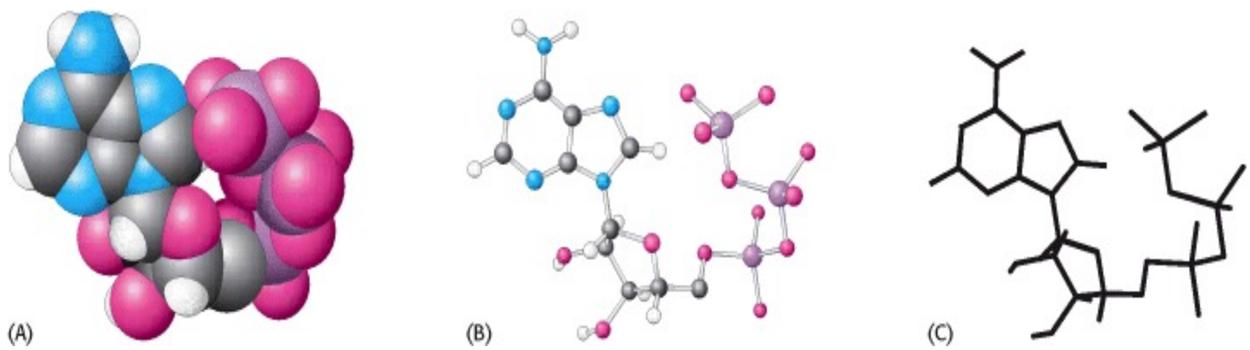

Figure 5 - Representations of Adenosine-Triphosphate (Berg et al., 2002)

a) Space-filling b) ball-and-stick c) skeletal

The first and default visualization mode is the traditional "ball-and-stick" model of visualization, where every atom (excluding hydrogens) is rendered as a sphere, and a stick like bond connects these atoms together (Berg et al., 2002). Double bonds were not rendered in the peptide bonds or in the R-groups containing them in order to reduce rendering complexity. This mode is the most expensive visualization mode available on the application, but provides the most traditional view of proteins for students, akin to ball-and-stick kits which can be used to construct molecules.

The second visualization mode available displays only the bonds connecting the atoms, and no atoms. This visualization mode was inspired by *skeletal* models (Berg et al., 2002), in which carbons are implicit at junctions of the lines and no spherical atoms are present. In the application, this visualization technique allows one to remove the atoms and observe the skeletal structure of the protein. The benefits to this visualization technique are one can see past the ‘clutter’ of the atoms, and observe the core structure represented in the backbone and R-groups of the protein. An additional benefit of this mode is it drastically cuts down the processing cost, and allows larger proteins to be visualized without software slowdown.

The final visualization mode is based off of a *space-filling* model (Berg et al., 2002). This model emulates the large spheres of a space-filling representation, but differs in some ways. Firstly, the applications space-filling representation only renders the peptide backbone of the protein, and does not render any atoms in the R-groups. It also increases the radius of the backbone atoms so they render as larger spheres. R-groups were excluded because the purpose of this visualization in the software was to reduce rendering complexity, as well as provide a view where a user can observe a “streamlined” representation of the proteins 3D structure. For example, in the figure below a protein is represented in all three visualization modes.

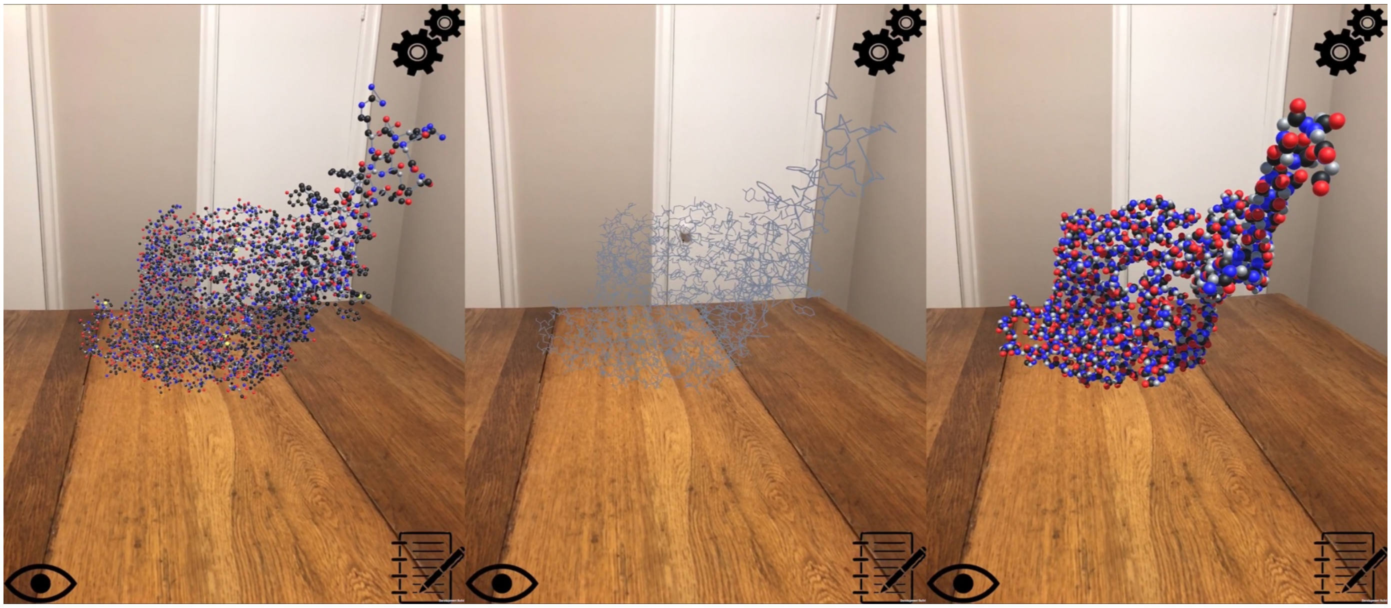

Figure 6 - Three Visualization Modes Offered in The Application (Left to Right: Ball and Stick, Back Bone, Space Filling View)

In the space-filling mode, the general channel structure is still visible and apparent, although some specify is lost without the R-groups. This visualization mode was indented to remove some of the extraneous processing from the model, and allow students to process what could be considered the most essential components of the proteins structure, its backbone. It is important to note that this visualization mode allows one to observe the general structure without the R-groups, because the model it is rendering is based off of a completely folded protein; one could not remove R-groups from a semi-folded protein and expect to see the general structure because the R-groups are essential to its folding (Sosnick et al., 1994). The liberty in visualization this mode takes is to remove rendering complexity and provide a most essential, basic, visualization mode.

There are many different additional ways in which the computational efficiency of the application could have been improved but they are beyond the scope of this paper.

3.3 Differences to Existing Software

The AR application designed for this research is not the first protein visualization software available, however it does have key differences to those that exist already. Several software's, some of which are open source, such as JMol, a browser based protein viewer (http://jmol.sourceforge.net/). This software allows users in their browser to rotate and view proteins, highlight various residues and regions, and use various visualization modes. The software developed for this research borrows ideas from JMol and other open source molecular viewers such as PyMol (http://pymol.org) and SWISS-PDB Viewer (Guex and Peitsch, 1997). PyMol is a library for the python programming language, while the SWISS-PDB viewer is an older piece of software that uses protein database files to generate molecular graphics. The software for this thesis has many of the same visualization features, such as the viewing modes, and its backend is dependent on protein database files. The major difference in this software solution is the platform; this previous software's either run in a computer browser (such as JMol), in a programming language environment (such as PyMol), or as standalone exactable software for Windows and Mac/Linux operating systems (such as SWISS-PDB). The software developed for this research runs in an iOS or android environment on a tablet or smartphone, and has the visualization functionality and benefits of augmented reality. Our software has the portability and integration of new computer vision techniques used in AR that the previous software's do not. The other major difference is the intended use of the software. Ours was developed with pedagogy and education in mind, so it has the functionality to include lessons and animations, which the previous software's do not include. The usage of lessons and the educational focus of our software is discussed in the next section.

3.4 Lessons in AR

The purpose of the designed application is two-fold: firstly, it is to allow for a unique visualization method of proteins that respects their 3D structure and provides students a new opportunity to observe and manipulate these structures in real space. The second purpose is to allow for unique, individual lesson modules that could be used to teach specific lessons on specific proteins, depending on which protein is rendered. We believe that these built-in lessons will allow students to learn specific material more effectively, and guide the use of the AR experience in such a way that is conducive to retention and understanding. Based on the previous literature discussed earlier, this focused approach may help alleviate distraction, increase novelty, and demonstrate the educational strengths of augmented reality, e.g. the ability to visualize and interact with abstract concepts and structures (like proteins) in a student's own real-world.

The software allows for individual image anchors to be detected in the environment; this is a function integrated into the arKit framework, that also exists in other augmented reality frameworks (such as Andorid's arCore). These image anchors can be any image the programmer decides on, and for the purpose of this study, we designed three image anchor "cards". Each of these cards has a certain protein programmed to render upon detection, and specific lesson animations, functions and tool tips can be registered to each card. Each card then acts as a unique self-contained lesson.

3.5 Developed AR Lesson Modules

Three lessons were created for the purpose of the studies experiment; these lessons focus on a category of proteins called *ion channels* (Alberts et al., 2002). Although three lessons were created, only one lesson was used in the actual study because going through all 3 lessons was found to be time consuming and distracting; in pilot trials having participants jumping from one lesson to another in a constrained manner was not optimal. In addition to this, all of the lessons were based on categories of ion channels, so one lesson was hypothesized to be sufficient. There are three major categories of ion channels: non-gated (leakage) channels, voltage-gated channels, and ligand-gated channels (Alberts et al., 2002). The channel used for the study was the non-gated ion channel. A description of each of the channels is in the following table, table 3 (All information taken from Alberts et al., 2002 unless otherwise noted):

Channel Type	**Description**	**PDB Code**
Non-Gated Ion Channel	Non-gated channels allows ions to slowly enter and exit the channel at all times to maintain internal charge equilibrium	1BL8
Voltage Gated Ion Channel	Voltage gated ion channels only allow flow of ions when the internal charge of the cell forces a structural change in the channel, normally by ejecting a metal ion that was impeding ion flow	4DXW

Ligand Gated Ion Channel	Ligand gated channels only allow ion flow when a ligand (molecule, drug, etc) interacts with the proteins *active site*, a special region of the protein evolved to interact with its ligand. This causes a structural change that allows ion flow	1OED

Table 3– Summary of Ion Channel Categories

The experiment outlined in the section below describes the study we will conduct.

3.6 Experimental Design

Students were recruited from an undergraduate level biochemistry class and additional students participated on their own accord without recruitment. Recruited students were assigned to alternating groups in the order they participated in the study; the experimental and control group. The control group completed an entrance quiz for demographics information, and then were provided with a short write up on ion channels, followed by a quiz on the written material and an exit questionnaire. The experimental group received all the same conditions, but before the quiz on the written material, were able to go through the lessons provided on the AR application, followed by the quiz and questionnaire then the exit. This experimental design, along with all forms and documents, were approved by the Laurentian University Ethics Research Board (approval form included in appendix).

The study period took place over 2 weeks, where recruited students were scheduled for 30 minute blocks. 6 Students were not recruited from the undergraduate class and reached out to the investigator independently to participate in the study. The study took place in the *Human Computer Interaction Learning Laboratory* located at Laurentian University. The laboratory was a small room with a single table and chair for the participants to work at, and a chair near the entrance for the investigator to sit at and observe. A diagram of the testing room is shown below:

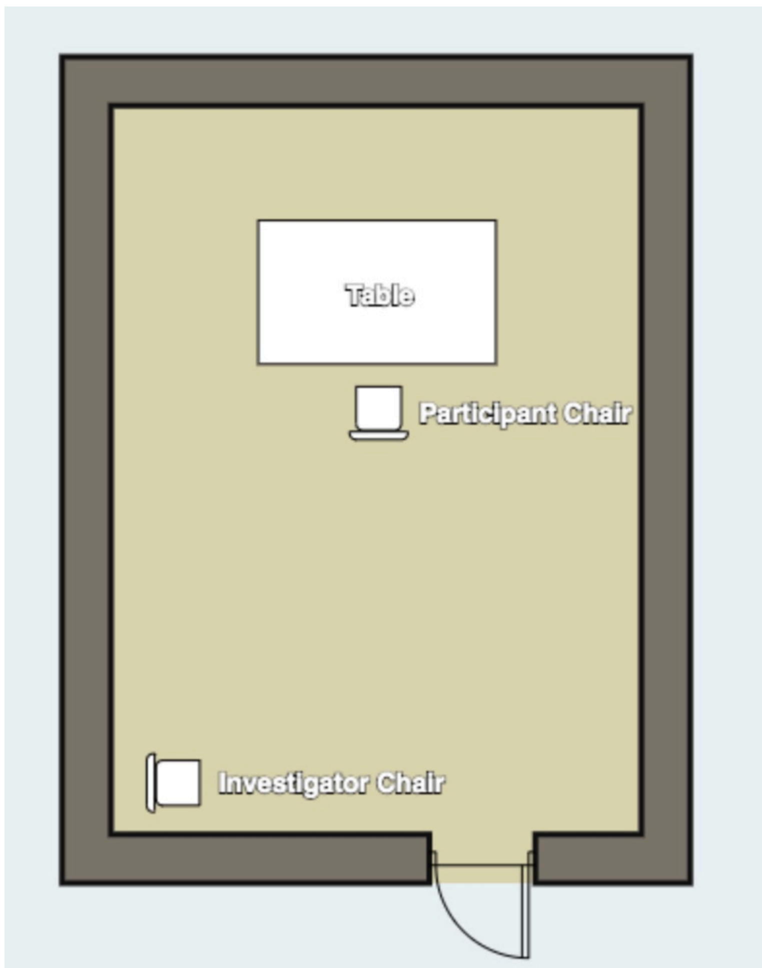

Figure 7 – Floor Plan of the Testing Room

One of the factors we are observing is students cognitive load, a measure of cognitive burden developed by Paas and Van Merriënboer (1993). Paas and Van Merriënboer describe cognitive load as "...may be defined as the total amount of controlled cognitive processing in which a subject is engaged" (1993). Similarly, Paas and Van Merriënboer presented the cognitive load scale (CLS), a quantitative metric of ones cognitive burden during a task (Paas and Van Merriënboer, 1993). This scale only requires a self reported measure of cognitive burden from a participant between 1 and 9, where 1 is lowest possible cognitive load and 9 is highest. In their paper, they present a means of calculating an *E* score, the cognitive *effort* score of the participant. The following figure 8 represents the distribution of possible E-Scores and their effect on cognition

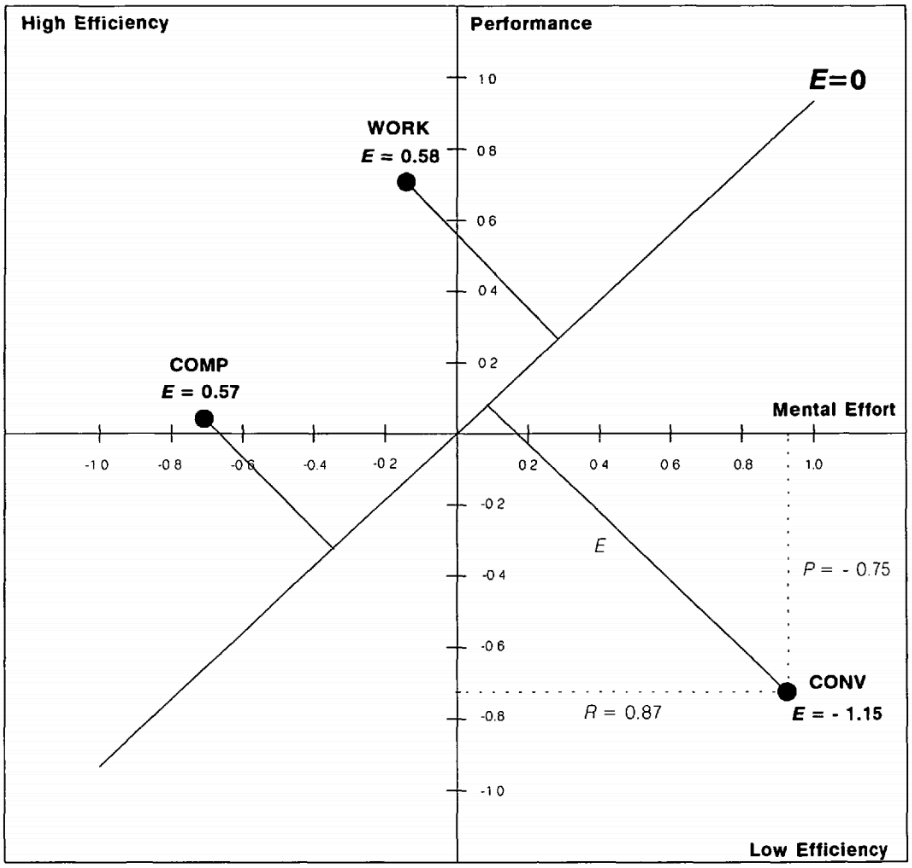

Figure 8 – Possible Distributions of calculated E-scores (Paas and Van Merriënboer, 1993)

Participants in our study were asked to self report their cognitive load after the experimental treatment is complete, on a scale of 1 – 9. The CLS was validated by Siti et al (2016) as statistically sound in the factors of cognitive load it measures. The CLS was also used in Küçük's et al (2016) study on the effects of augmented reality on anatomy education, and demonstrated that AR can increase test scores while simultaneously decreasing *E* scores. Based on these previous results, we expect our study to demonstrate increased experimental test scores as well as decreased experimental *E* scores.

In addition to measuring test scores and effort scores, certain demographic questions were asked of the students. They were asked if they are biology students (who would presumably be more familiar with proteins than others), what their comfort level with proteins are, how excited they were about the lesson once it is over, and how they would rate the written material and/or AR application on its ability to transfer knowledge to them. We hypothesize that students, regardless of there background or comfort with biology, will rate the AR application more exciting than just written material.

We hypothesize the experimental group will have higher quiz scores because of the AR lessons facilitating greater understanding and retention. In addition to this, we believe that the experimental group will have higher self reported excitement scores, and lower effort scores.

In summary, during this experiment, we will be attempting to disprove three separate null hypotheses:

1) Using the AR applications has no effect on test scores

2) Using the AR application has no effect on cognitive-load effort scores

3) Using the AR application has no effect on self reported excitement

4 Results

Thirty students (N = 30) took part in the study over the course of two weeks. The students were split into two groups, an experimental group and a control group. Of these 30 students, 24 were undergraduate biology students, while the remaining 6 were computer science and engineering students who requested to participate in the study. All of the students began the study by signing for informed consent to participate, and filled out a basic demographics questionnaire. In this questionnaire, they were asked what their comfort level with the concept of proteins was on a scale of 1-5 (1 being no knowledge of proteins and 5 being a sophisticated knowledge of proteins). The experimental group (N = 15) on average had a comfort level of 2.92 while the control group (N = 15) had an average comfort level of 3.42. There was no way to control for this factor as students were alternated between experimental and control groups as they arrived for the study. 8 of the 15 participants in the experimental group had used an AR application before, while 7 from the control group had used an AR application before.

4.1 Test-Scores Results

The participants then read an approximately 2-page report on channel proteins, their structure and their function. After reading, the experimental group had time to use the application while the control group did not. A short 16-point test was administered, consisting of 5 short answer questions, 5 true or false and 6 multiple choice questions. The control group on average scored 83.93% on the quiz while the experimental group scored on average 93.30%. The Z-scores were calculated for these scores, with the experimental group having an average z = 0.488 and the control group's average z = -0.373. An analysis of variance (ANOVA) was performed on the standardized z-scores for both treatments tests ($a = 0.05$) leading to a p-value = 0.0197. In addition to the ANOVA, a Paired Two-Sample t-Test was performed on the results. The mean experimental z-scores for tests (M = 0.488) and mean control z-scores for test (M = -0.373) with conditions a=0.05, t(15) = 2.541, and t-critical two-tail = 2.160. Because t-critical is less than our *t* value, these results are statistically significant. The t-test and ANOVA results both allow us to reject the null hypothesis (1) that is the AR application will have no effect on test scores. These results indicate that there is a significant positive effect on test scores when the AR application was used in conjunction with written material.

4.2 Effort Scores Results

After the test was written, students were asked to rate their cognitive load on a scale of 1-9. The average experimental cognitive load was 5.35 control while the average was 5.71. When the z-scores for raw cognitive load scores were calculated and an ANOVA was performed, there was no statistically significant results ($a = 0.05,\ p > a$). The raw cognitive load scores should not be considered however, as outlined by Paas and Van Merriënboer, they must be calculated into E scores; the process of generating E scores is described elsewhere (1993). Once 15 individual E-scores are calculated for each group, an ANOVA was performed, and was statistically significant, albeit with a higher alpha value used ($a = 0.1, p = 0.083\ \ p < a$). A Two-tailed t-test was also performed on this dataset. The mean experimental z-scores for tests (M = 0.420) and mean control z-scores for test (M = -0.337) with conditions a=0.10, t(15) = 2.088, and t-critical two-tail = 1.771. Since t-critical is less than our *t* value, we can once again say these results are statistically significant. The ANOVA and t-test results allow the null hypothesis (2) to be rejected, that is that the AR application would have no effect on E scores. This indicates that the calculated E scores of participants is significantly lower when they had the experimental treatment (AR application and writing) over the control (just writing). Statistics were also performed (ANOVA and T-test) on the raw cognitive load scores before they were treated to be effort scores; these results are included at the end of this section in table 4 and table 5 respectively. The raw scores had no statistically significant differences between groups.

Below is a figure of the average effort scores for each group, plotted as described by by Paas and Van Merriënboer (1993).

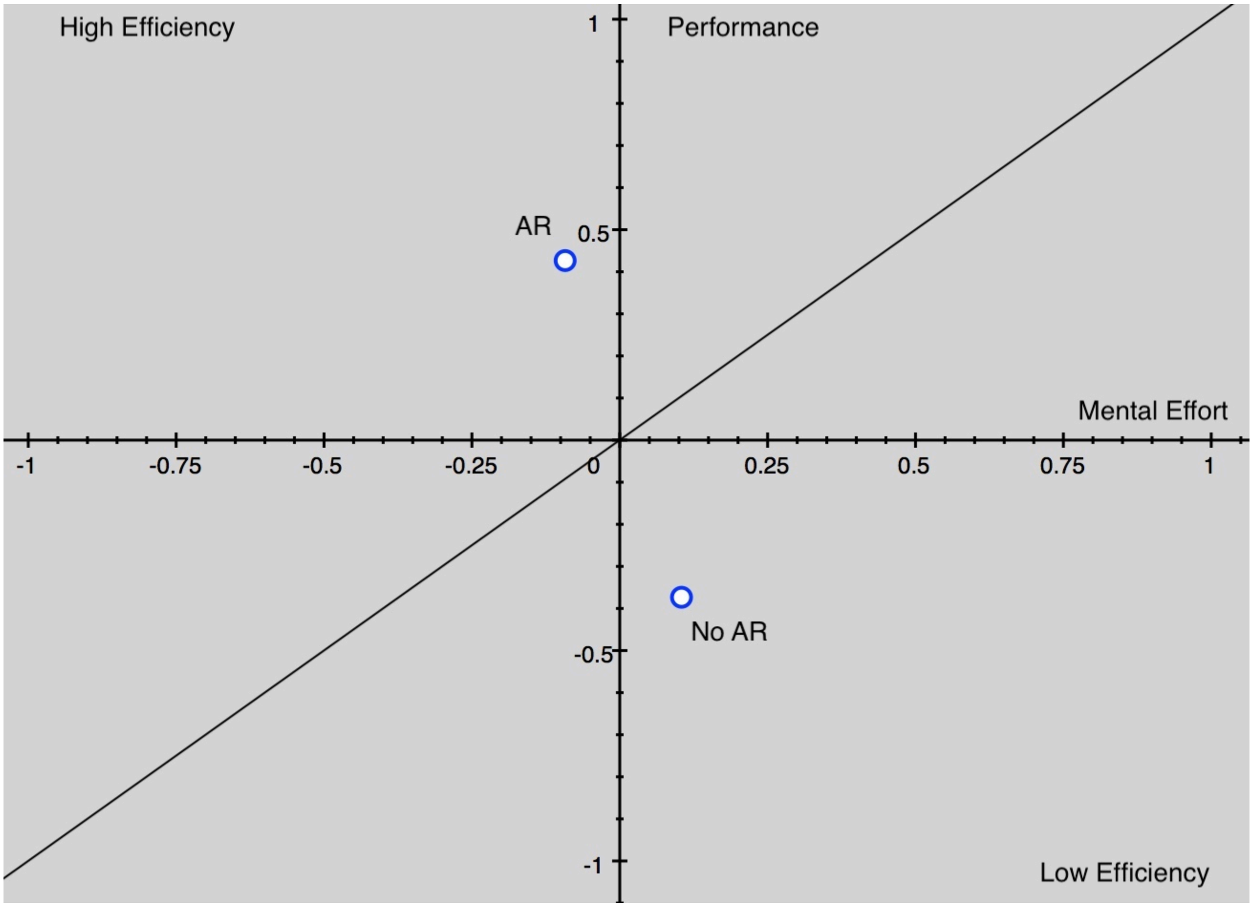

Figure 9 – Distributions of E-scores after testing (AR is experimental; no AR is control)

4.3 Excitement Ratings Results

The final result from the study is the students self-reported excitement, which was asked in the final questionnaire along with their cognitive load. Students reported excitement on a scale of 1-5, with 1 being not exciting at all and 5 being very exciting. The average excitement rating for the experimental group was 4 while the average excitement rating for the control group was 2.714. An ANOVA was performed, and the results were statistically significant ($a = 0.01, p = 0.00185\ \ p < a$). Additionally, a t-test was performed. The mean experimental excitement scores for the study (M = 4) and mean control excitement scores (M = 2.714) with conditions a=0.01, t(15) = 3.026, and t-critical two-tail = 3.012. Since t-critical is less than our *t* value, we can state these results are statistically significant. The outcome of both the ANOVA and the t-test allow the null hypothesis (3) to be rejected, and we can say the AR application significantly made students self report greater excitement about the lesson.

4.4 Power Analysis

A post-hoc power test was performed using the test scores as a metric. This analysis was done to determine the power of our test, and if we correctly rejected the null hypothesis. Since we rejected all 3 null hypothesis, we have the possibility of causing a type I error, or the incorrect rejection of a true null hypothesis (Rosner, 2011). Adequate statistical power in a post-hoc analysis is a means of validating our rejection of the null-hypothesis. The experimental group's average score, $u_e = 93.30$ ($SD_e = 7.541$) and the control groups average score, $u_c = 83.92$ ($SD_c = 11.93$) were inputted into the post-hoc power formula as outlined in texts (Rosner, 2011). For the test-scores, we calculated a post-hoc power of 73.2%. This value runs slightly below the accepted standard power of 80%, however it is still an adequate power for our research. This research could have benefited from a pre-test sample size analysis, in order to achieve a power of 80%. Some statisticians highlight that post-hoc analysis do not change the measured outcomes, but rather indicate if we as researchers are correctly rejecting or accepting the null-hypothesis, and to what degree we are likely to be correct in this rejection (Lenth,2007). Due the to the strong, positive rejection of the null for all 3 of our measured outcomes, and the adequate calculated power, it is likely we did not make a type I error. As stated previously however, a sample size could be calculated before testing begins in order to ensure enough participants are recruited to give a power of 80% or greater (Rosner, 2011).

4.5 Other Results

Both the experimental and control group had to read the same written material, and they were asked to rate its effectiveness from 1 to 5 (1 being totally ineffective and 5 being greatly effective at disseminating information to them). The average rating for the experimental group was 3.93 while the average rating for the control group was 3.79. An ANOVA was performed on both treatments scores ($a = 0.10,\ p = 0.626\ \ p > a$), and there were no significant differences found. No t-test was performed, and we must accept the null hypothesis that using the AR application had no effect on the subjective rating of the written material. Only the experimental group was able to rate the effectiveness of the AR application in disseminating information to them (on a scale of 1 to 5), and on average the experimental group rated it a 4.5. This information cannot be measured against the control group however, so no further analysis was performed.

All statistics were performed using Microsoft Excel 2016 Data Analysis function. The results of the ANOVA and T-tests performed on all data are included below in table 4 and 5 respectively:

Factor	**Alpha (a)**	**P-Value (p)**	**Reject Null (p < a)**
Test Scores	0.05	0.0197	Yes
Effort Scores	0.1	0.083	Yes
Excitement	0.01	0.00185	Yes

Cognitive Load Rating (raw)	0.1	0.611	No

Table 4 – Summarized Results of ANOVA on Various Factors

Factor	**T-stat**	**T-Critical**	**Reject Null (T-Critical < T-Stat)**
Test Scores	2.541	2.16	Yes
Effort Scores	2.088	1.771	Yes
Excitement	3.026	3.012	Yes
Cognitive Load Rating (raw)	-0.55	2.16	No

Table 5– Summarized Results of T-Test on Various Factors

5 Discussion

This application was designed for use in a classroom, based on the noted effectiveness of other AR applications across various subjects being used in the classroom setting (Saidin et al., 2015). The study performed for this thesis allowed for the evaluation of its effectiveness in a pseudo-classroom experience. The primary questions being asked before the study began was can this application increase test scores, can it lower effort scores, and can it positively impact attitudes such as excitement, about the lesson? As shown in the results section, all hypothesis's were validated, with significantly higher test scores, significantly lower effort scores, and significantly higher excitement scores, as outcomes from the experimental group. These results were expected, not only because of previous studies performed using AR applications, but because of the idea that diversifying learning models and approaches will always be of benefits to students (Bonwell and Eison,1991). The three outcomes will be discussed in greater detail below.

5.1 Test-Scores Discussion

The tests were marked out of 16 points, 5 short answer, 5 true or false and 6 multiple choice questions, all pertaining to channel proteins. The participants were able to ask questions for clarification, but no assistance was given to them while filling out the test, nor were they allowed any outside devices. As stated above, the results were statistically significant when an ANOVA was performed ($a = 0.05$), as well as a two tailed t-test ($a = 0.05$). The statistical analysis lead to results that allow us to reject our null hypothesis that the AR application has no effect on test scores. This result seems intuitive upon reflection, as offering a randomly selected group of students an interactive model would increase there generative learning (Mayer, 2010). The AR application allowed the concepts the students read about in the provided written material to be solidified in a tangible, visually concrete way via the application. This is highlighted by comments made by participants during the study. One participant, a male undergraduate biology student said “you can use the [application] to line up the channel and really observe that it is a channel…this was not entirely clear from just the [written material]”. This student had positioned the tablet in such a way where he was looking “straight down the barrel” of the protein channel, as it were. Figure 9 below illustrates this point:

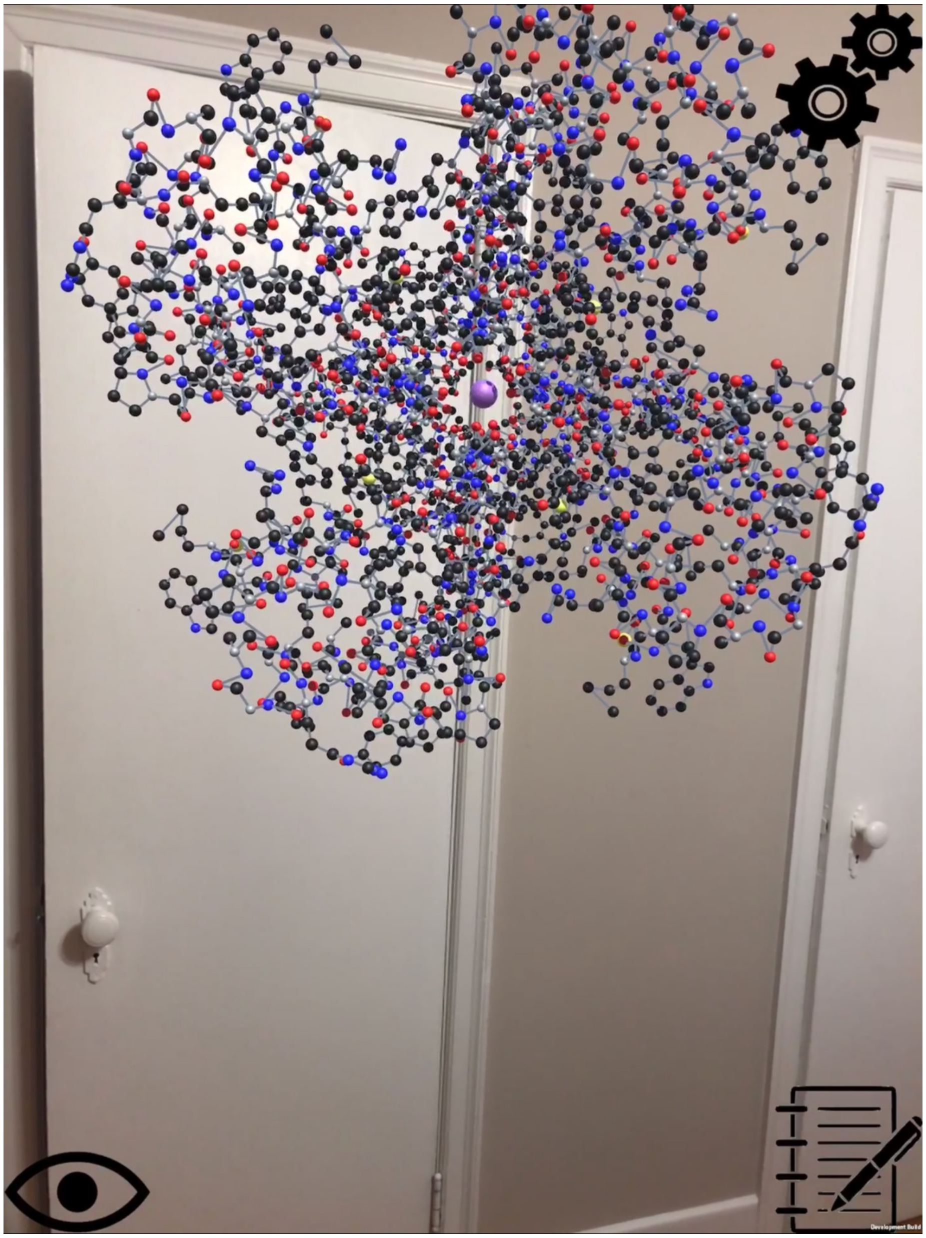

Figure 10 - A potassium channel lined up so the purple potassium ion is in the channel portion of the protein

Another participant, a male non-biology student, with no prior experience with proteins said the information "clicked" once the tablet was used and he could walk around the protein and take his time observing its 3D structure. These two examples help to demonstrate how the application reduced extraneous processing, such as maintaining a mental model of the 3D structure, and allowed generative processing to occur by utilizing the technology and having the 3D model be created outside of the student's mental model. In addition to this allowing the participants to read the written material and immediately follow it with the application may have allowed for even greater generative processing to occur; enough so that without the application the participants did significantly worse on the test.

The application usage may have also impacted different learning styles more so than others, reflecting the results we collected. As discussed in a previous section, active learners learn best when they are actively engaged in the learning experience (Felder and Silverman, 1988). Using this application forced the participants to engage their attention and focus on using the app and observing the model in an active manner, they were not just passively reading. The participants had to adjust their tablet position and their own position in space in order to follow along with the AR lesson, and they took part in observing the ions flow in a more active way than those who just read the written material. In addition to active learners, inductive learners may have benefited from the hands on nature of the lessons, which allowed them to explore the protein structure at there own pace, and make observations and discoveries themselves (Felder and Silverman, 1988). During the study, the "lining up" of the channel represented an inductive approach to learning about protein channels, where the observations and connections were organically formed by the participant, and not dictated in the written material solely. Participants were able to cycle through the 3 visualization modes available on the application. All participants cycled through all displays at least once, and often times alternated displays. Having this option may have benefited visual learners who require alternative viewing options. It also may have been of benefit to inductive learners, who were able to make inferences and learn based on observing various perspectives of the protein.

Both groups had similar ratings for the effectiveness of the written material (experimental = 3.93, control = 3.79), and the control group actually had a greater self reported understanding about proteins (experimental = 2.92, control = 3.42). ?) This is an interesting result, as the control group did not achieve significantly higher test scores. This discrepancy between initial knowledge is not congruent with the experimental groups significantly better test scores, and only highlights the effectiveness of an AR application when used from a pedagogical perspective.

5.2 Effort-Scores Discussion

The calculation of the effort scores was performed as described by Pass and Van Merriënboer (1993). Effort scores are an interesting metric to use when studying student performance, as they take into account both their actual academic achievements (in this instance, test scores) as well as their subjective cognitive load rating. The results for this factor where statistically the weakest of all of the outcomes; an alpha = 0.10 was used in both an ANOVA and a t-test for means to achieve a statistically significant result. The visualization of both groups average E-scores can be observed in figure 9. In the figure, the experimental group is found within the high efficiency quadrant, while the control is in the low efficiency quadrant. This indicates that the experimental group used their cognitive resources more effectively and efficiently than the control group did. In addition, the experimental group has a higher performance value (the y-axis) and a lower mental effort rating (the x-axis) than the control group. These results are congruent with what we expected, although somewhat weaker of a statistical association than the other outcomes. We are unable to comment if this association would have been stronger with a larger sample size, although this could be addressed in future studies.

Despite that the weaker statistical association than other outcomes, this outcome is very positive for promoting the usage of AR applications in the classroom. Reducing cognitive load can help reduce the extraneous processing associated with learning, as well as increase efficiency of learning more material (Hayes, 2010). One of the challenges of education is presenting the material in a manner which is accurate and correct, but digestible for the audience who may not completely understand the implications or scope of what they are learning. Utilizing a technology supplementary to traditional lessons, such as AR applications can increase efficiency and performance, as we have demonstrated. Increasing the number of learning modalities available to students is paramount in lowering their cognitive load, and educators can take advantage of the diversity and applicability of AR applications to do just this (Kirschner,2002). Our research shows that understanding of even relatively complex topics, such as protein structure and its relationship to function, benefits from this increasing of modalities.

5.3 Excitement About the Lesson

The strongest statistical outcome from this study was the excitement participants had regarding the lesson itself. When asked to rate their excitement from 1-5 about the lesson, the experimental group had an average rating of 4 while the control had an average rating of 2.714. When both an ANOVA and t-test for paired means was performed with an alpha = 0.01, the results were statistically significant in both cases. Participants who used the application were excited about using it, both empirically and qualitatively. Eight of the 15 participants from the experimental group left positive comments on their final questionnaire about how “cool” or “fun” or “exciting” the application was. Those who didn’t leave comments made positive verbal remarks during the actual study when first using the application (“wow” or “cool” or other positive sentiments). These remarks were written down by the investigator during each participant’s trial.

Novelty may have something to do with the excitement students showed; no student that participated in this study had ever used an AR application for a scientific purpose before. It is difficult to discuss their excitement without acknowledging how novelty may have impacted this. Despite the possibility of novelty being a confounding factor, it is clear that the excitement participants had about the application was translated to attentiveness and an openness to learning, as reflected in the test scores and effort scores. This understates one of the principals of active learning, that excitement and being engaged with the material translates to better academic outcomes for students (Bonwell and Eison,1991). If a student is excited about the material they are learning about they will be more willing to learn that material, both consciously and subconsciously through learning pathways affected by mood (Reschly et al., 2008). Whether this excitement is because the material itself is stimulating, or that technologies are offering a perspective that is more stimulating than the traditional methods, excitement should never be unwanted in a learning setting. Some research has directly indicated that positive emotions, such as excitement, may increase engagement and long term success in students (Rechly et al., 2008).

This potential benefit of excitement is highlighted once again by the results of this study. The experimental group did better on all three outcomes, and was *much* more excited about the material than the control group. If they did better solely because of the excitement cannot be commented on, but its inclusion is likely a compounding factor in the success of the experimental group.

Although the control group did not use the application during the study, after they completed participants were given the option of using the AR application and asking questions if they had any. Several control group participants explicitly stated that they wished they were able to use the application before writing the test as they claimed it would have helped in some way. The subjective reactions were similar to those in the experimental group; participants thought the application was interesting and exciting. Although no data was recorded at this point, the control groups feedback and comments were noted by the investigator.

5.4 Technical Comments About the Application

Participants voiced several comments about the application during the testing. Some of the positive, educational-based comments were discussed above, but students also had technical comments regarding the application. Some participants chose to stand up and walk around the model (which was rendered on a table) in order to observe it, while some remained seated and used their fingers to drag and adjust the model until it was at the appropriate location for them. Some students who remained seated requested a spin function, where the protein would rotate along a vertical axis. This feature was removed early on in the development of the software as it was intended that students move themselves around the protein, rather than the protein rotating statically in one spot. The ability for the students to move around the protein was chosen because it is one of the more unique features to ARKit; the ability for the model to maintain its position in 3D space while you move around it. After comments made by participants, a rotation button could certainly be re-implemented to allow users to rotate the protein along a selected axis. This feature would have to allow the user to select the axis however, as the diverse shapes and sizes of proteins means that the plane of rotation will not be the same for all proteins.

Some participants also voiced a desire to obscure the whole protein, and render only selected residues. This feature could be implemented as each residue is its own object in the Unity engine, which can have its graphics renderer turned on or off at will. This feature would require some sort of list of residues to be available to the user however, as well as a means of selecting multiple regions at once while obscuring the rest of the protein. This feature would be possible but would require additional scripts to be written that were not complete at the time this study was performed.

A single participant asked if multiple proteins could be rendered at once, and although this is possible, it can greatly reduce the performance of the application. This would be a technical challenge to implement, as the sheer size of the proteins and the number of rendered objects is so high that multiple proteins will easily drain the available processing power of the tablet. Occlusion culling was a technique utilized in this project, where objects that are not currently in the field of view of the camera were not rendered, and then dynamically rendered as they come into view. Further optimization of this technique, as well as various other performance enhancing tricks would have to be implemented in order to successfully model protein-protein interactions.

5.5 AR and Learning Styles

As discussed above, the successful rejection of the null hypothesis for all 3 of our measured outcome is a positive, but an unsurprising result. The usage of novel technologies is not new to education, as technologies can offer distinct and unique perspectives that would not be possible otherwise. Public schools and University settings often push forward the use of technology for education, as we have seen in the past with desktop computers, laptops, projectors, and more recently, smartphones and tablets. AR is an interesting technology for education because augmented reality itself is not a tangible piece of technology, it is software that is made possible due to recent advances in smartphone and tablet processing power and computer vision. For example, although tablets and smartphones have had cameras since they were introduced, only recently has processing power been great enough to allow for live video processing to create planes in the natural environment for 3D models to be rendered upon (Apple, 2018).

The diversity of software applications, and innovations versus hardware, is one of the factors that makes AR such an appealing platform for educational development on. The real world can be interlaced with *any* sort of 3D model and animation the developer would like, allowing for a diversity of types of applications and pedagogical approaches. This is of great benefit for the large variety of learners in classrooms. As discussed above, Felder and Silverman's five type of learners can all in some way potentially benefit from the diversity of AR applications. A primarily sensing student thrives off of hands on examples (Felder and Silverman, 1988). An AR application provides some level of tangible, hands on immersion because of the 3D spatial nature of the application (Thornton, Ernst and Clark, 2012). This is of great benefit to educators who can utilize a variety of AR applications to provide sensors with a wide array of hands on AR lessons and applications. In our case, with proteins being the topic covered, sensors would likely never have the opportunity to manipulate a life-size protein with their own hands, all observation would have to be done with a mouse in a traditional visualizer, or potentially with a physical model if it is available to the student. Even if the model is available to the student, they are costly, and they would likely not be able to have multiple models as they can with the AR application.

5.6 Limitations of the Study

There were some limitations of the study that need to be addressed. Firstly, in the study, only 1 pre-made lesson (Non-gated ion channels) was given to the students, despite them being quizzed on 3 categories of ion channels (Non-gated, ligand gated, and voltage gated). This was done for several reasons. Firstly, having participants use all three pre-made lessons drastically increased the time of the study as well as its complexity. We felt that having students rapidly switch from lesson to lesson and then write the test would have left them more focused on using the application correctly in the allocated time than on the actual content. In addition to this, the written material provided had enough information within it to allow students to get 100% on the quiz (as to not be unfair to the control group). Because of this, there was no drastic need to make sure the experimental group had interactive lessons on all 3 types of channel proteins; we felt that one well done lesson would reinforce concepts common to all three types of channel proteins discussed. The channel proteins discussed did not differ in their channel properties (they all allowed ions to flow in some direction through the channel), but differed in their mechanism of opening and closing (Alberts et al., 2002). We felt that showing them the non-gated lesson was sufficient information to not only do well on the test, but reinforce the concepts about ligand gated and voltage gated channels they had read about.

One of the other challenges that made us select using only one lessons was the time constraint of the study; participants were only coming in for one session. If a consistent group of students could be recruited and come back for several sessions, we could have used all of the lessons individually and evaluate the AR application over time and over various lessons. Since only one session was available for our experimental design, the decision was made to use only the one lesson that could be abstracted and applied to the other two categories of channels. If this study were to be repeated, a long term study involving several lessons and test scores and E-scores over several sessions could have been tabulated.

6 Conclusion and Future Directions

6.1 Future Directions

This research has highlighted the value of augmented reality technologies in the classroom, and their adaptability to topics as complex as protein structure. Our significant and positive results highlight a need for further study into this area of human computer interaction, and more analysis on how to create effective AR applications, as well as what exactly makes an AR application optimally effective, must be performed. This research could be continued and expanded by implementing suggested features into the protein AR application and having more long term studies be performed. Additionally, this research could expand by creating a different AR application that covers a different academic topic, and evaluating its effectiveness.

In this study, we observed the effectiveness of a protein visualizing AR application, and how interactive lessons and animations can help aid students learning. A future direction may be inquiring what subjects benefit best from AR applications, and if certain humanities like writing and art may also benefit as much as biochemistry and science education did from this study. Some recent studies indicate that even language acquisition may benefit from the use of AR technologies (Santos et al., 2016).

One of the more technical directions this research may take in the future is designing and implementing more efficient ways of visualizing protein-protein or protein-ligand interactions in an AR environment. Molecular dynamics is a sub-field of computational sciences and chemistry, where computer systems perform simulations of molecules or small chemical compounds and their interactions with other molecules or atoms (Karplus and Petsko, 1990). Although it would not be feasible (or practical) to run these simulations directly on a tablet, in the future applications like ours could utilize known molecular dynamics results to inform the animations and lessons and highlight interactions in AR that would normally not be viewable. Molecular dynamics is an important component of pharmaceutical drug design (Griend, 1990), which may be an avenue of interest for AR visualization in the future. Drug designers must understand the 3D structure and topology of a protein to create a specific molecule to interact with it, and AR provides an interesting and novel means of visualizing proteins. Pharmaceutical design is a potential direction of this research separate from education.

6.2 Conclusion

Throughout the course of this research we have accomplished several goals and adapted our work to reflect the current academic research performed on augmented reality technologies and pedagogical approaches. We have developed a protein visualizer designed for use with a virtual reality headset, we have adapted and altered that software into an augmented reality tablet based software, and we have included lessons and visualization options to help students learn better. The complexity and nuances of protein structures can be difficult for students to grasp, especially if they perform best with hands on instructions in order to learn most efficiently. In this research, we have demonstrated that augmented reality software is a viable option for not only increasing academic achievement when studying protein structure and function, but decreases students cognitive load and increased excitement about learning greatly.

Augmented reality software is burgeoning, and its applications in education cannot be ignored. This research has shown that not only can augmented reality software tackle complex topics, such as what we accomplished with our protein AR application, but the application can be of a real benefit to students and educators alike. As tablet and camera hardware continues to be pushed forward, so will the potential of AR applications like ours, and their viability for real world use will increase greatly as time moves on. The need for understanding Human-Computer interaction is rapidly growing, and studying applications of software like we have emphasizes the need and importance of this research. The classroom of tomorrow will likely not look the way it does now, as students utilize technology and software that helps promote their own learning based on their unique approach and style. Augmented reality applications will be of the utmost importance to this educational revolution, and will impact how we interact with our technology moving forward.

References

Alberts B, Johnson A, Lewis J, et al. Molecular Biology of the Cell. 4th edition. New York: Garland Science; 2002. Principles of Membrane Transport. Available from: https://www.ncbi.nlm.nih.gov/books/NBK26815/

Apple. (2018). Developer Documentation on ARKit.

Berg JM, Tymoczko JL, Stryer L. Biochemistry. 5th edition. New York: W H Freeman; 2002. Appendix: Depicting Molecular Structures. Available from: https://www.ncbi.nlm.nih.gov/books/NBK22407/

Bonwell, C. C., & Eison, J. A. (1991). *Active Learning: Creating Excitement in the Classroom. 1991 ASHE-ERIC Higher Education Reports*. ERIC Clearinghouse on Higher Education, The George Washington University, One Dupont Circle, Suite 630, Washington, DC 20036-1183.

Cai, S., Chiang, F. K., Sun, Y., Lin, C., & Lee, J. J. (2017). Applications of augmented reality-based natural interactive learning in magnetic field instruction. *Interactive Learning Environments*, *25*(6), 778-791.

Di Serio, Á., Ibáñez, M. B., & Kloos, C. D. (2013). Impact of an augmented reality system on students' motivation for a visual art course. *Computers & Education*, *68*, 586-596.

Eaton, M. L. M., & Sheppard, S. D. (2014). Students' Persectives on Homework and Problem Sets in STEM Courses. *age*, *24*, 1.

Felder, R. M., & Brent, R. (2005). Understanding student differences. *Journal of engineering education*, 94(1), 57-72.

Felder, R. M., & Silverman, L. K. (1988). Learning and teaching styles in engineering education. *Engineering education*, 78(7), 674-681

Guex, N. and Peitsch, M.C. (1997) SWISS-MODEL and the Swiss-PdbViewer: An environment for comparative protein modeling**.** *Electrophoresis* **18**, 2714-2723.

Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. *Journal of computer assisted learning*, *22*(6), 392-404.

Hussein, M., & Nätterdal, C. (2015). The Benefits of Virtual Reality in Education-A comparision Study.

Iossi, L. (2013). Strategies for reducing math anxiety in post-secondary students

Johannes Huwer, and Johann Seibert, (2018): A New Way to Discover the Chemistry Laboratory: The Augmented Reality Laboratory-License. *World Journal of Chemical Education*, vol. 6, no. 3 124-128. doi: 10.12691/wjce-6-3-4.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of computer assisted learning*, *7*(2), 75-83.

Joo-Nagata, J., Abad, F. M., Giner, J. G. B., & García-Peñalvo, F. J. (2017). Augmented reality and pedestrian navigation through its implementation in m-learning and e-learning: Evaluation of an educational program in Chile. *Computers & Education*, *111*, 1-17.

Karplus, M., & Petsko, G. A. (1990). Molecular dynamics simulations in biology. *Nature*, *347*(6294), 631.

Kirschner, P. A. (2002). Cognitive load theory: Implications of cognitive load theory on the design of learning.

Küçük, S. , Kapakin, S. and Göktaş, Y. (2016), Learning anatomy via mobile augmented reality: Effects on achievement and cognitive load. *American Association of Anatomists, 9: 411-421.*

Lee, S., Kim, M. W., McDonough, I. M., Mendoza, J. S., & Kim, M. S. (2017). The Effects of Cell Phone Use and Emotion-regulation Style on College Students' Learning. Applied Cognitive Psychology, 31(3), 360-366.

Lenhart, A., Duggan, M., Perrin, A., Stepler, R., Rainie, H., & Parker, K. (2015). *Teens, social media & technology overview 2015* (pp. 04-09). Pew Research Center [Internet & American Life Project].

Lenth, R. V. (2007). Post hoc power: tables and commentary. *Iowa City: Department of Statistics and Actuarial Science, University of Iowa*.

Mayer, R. E. (2010). Applying the science of learning to medical education. *Medical education*, *44*(6), 543-549.

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, *70*, 29-40.

Pew Research Center. (2017). Mobile fact sheet. *Pew Research Center: Internet, Science & Tech*.

Millar, R. (1991). Why is science hard to learn?. *Journal of Computer Assisted Learning*, *7*(2), 66-74.

Paas G. W. C. and J. G. Van Merriënboer (1993), The Efficiency of Instructional Conditions: An Approach to Combine Mental Effort and Performance Measures.. *Human Factors.* Vol 35, Issue 4, pp. 737 – 743

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995, December). Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies* (Vol. 2351, pp. 282-293). International Society for Optics and Photonics.

Reschly, A. L., Huebner, E. S., Appleton, J. J., & Antaramian, S. (2008). Engagement as flourishing: The contribution of positive emotions and coping to adolescents' engagement at school and with learning. *Psychology in the Schools*, *45*(5), 419-431.

Rodriguez, F., Rivas, M. J., Matsumura, L. H., Warschauer, M., & Sato, B. K. (2018). How do students study in STEM courses? Findings from a light-touch intervention and its relevance for underrepresented students. *PloS one*, *13*(7), e0200767. doi:10.1371/journal.pone.0200767

Rosner, B (2011). *Fundamentals of Biostatistics*. 7th ed. Boston, MA: Brooks/Cole.

Rossing, J. P., Miller, W., Cecil, A. K., & Stamper, S. E. (2012). iLearning: The future of higher education? Student perceptions on learning with mobile tablets.

Santos, M. E. C., Taketomi, T., Yamamoto, G., Rodrigo, M. M. T., Sandor, C., & Kato, H. (2016). Augmented reality as multimedia: the case for situated vocabulary learning. *Research and Practice in Technology Enhanced Learning*, *11*(1), 4.

Saidin, N. F., Halim, N. D. A., & Yahaya, N. (2015). A review of research on augmented reality in education: advantages and applications. *International education studies*, *8*(13), 1.

Siti N.H. Hadie, Muhamad S.B. Yusoff. (2016) *Assessing the validity of the cognitive load scale in a problem-based learning setting.*Journal of Taibah University Medical Sciences, Volume 11, Issue 3.

Sosnick, T. R., Mayne, L., Hiller, R., & Englander, S. W. (1994). The barriers in protein folding. *Nature Structural and Molecular Biology*, *1*(3), 149.

StatCounter Global Stats. (2018). Mobile Vendor Market Share. http://gs.statcounter.com/vendor-market-share/mobile

Stothart, C., Mitchum, A., & Yehnert, C. (2015). The attentional cost of receiving a cell phone notification. *Journal of experimental psychology: human perception and performance*, *41*(4), 893.

The Protein Data Bank H.M. Berman, J. Westbrook, Z. Feng, G. Gilliland, T.N. Bhat, H. Weissig, I.N. Shindyalov, P.E. Bourne (2000) *Nucleic Acids Research*, 28: 235-242. doi:10.1093/nar/28.1.235

Thornton, T., Ernst, J. V., & Clark, A. C. (2012). Augmented reality as a visual and spatial learning tool in technology education. *Technology and Engineering Teacher*, *71*(8), 18-21.

Treagust, D. F., & Duit, R. (2008). Conceptual change: A discussion of theoretical, methodological and practical challenges for science education. *Cultural Studies of Science Education*, *3*(2), 297-328.

Tsai, Chia-Wen. (2017). The applications of augmented reality for universal access in online education. Universal Access in the Information Society. 10.1007/s10209-017-0589-x.

Vriend, G. (1990). WHAT IF: a molecular modeling and drug design program. *Journal of molecular graphics*, *8*(1), 52-56.

Ward, A. F., Duke, K., Gneezy, A., & Bos, M. W. (2017). Brain drain: the mere presence of one's own smartphone reduces available cognitive capacity. *Journal of the Association for Consumer Research*, *2*(2), 140-154.

Yuen, S. C. Y., Yaoyuneyong, G., & Johnson, E. (2011). Augmented reality: An overview and five directions for AR in education. *Journal of Educational Technology Development and Exchange (JETDE)*, *4*(1), 11.

Appendix A: Pre and Post Test Questionaire

PRE TESTING QUESTIONNAIRE

1) Gender: **Male** **Female** **Rather Not Say**

2) Age: **<18** **18-25** **26-35** **36-45** **45+**

3) Are you currently in some biological sciences (biology, biochemistry, biomed, etc) program? **Yes** **No**

4) Do you know what a protein is? **Yes** **No**

    a. If yes, what is your level of comfort ability with the concept of proteins

       (lowest)1 **2** **3** **4** **5(highest)**

5) Have you ever used an Augmented Reality (AR) program? (Ex: Pokemon Go)
   Yes **No**

    a. If yes, what program(s)? List below:

6) What is your preferred medium of learning? Select all that apply:
    a. Textbook/Written Material
    b. Computer/Laptop
    c. Smartphone
    d. Tablet
    e. Lecture
    f. Other (Please list):

7) What is your current/highest level of education?
    a. Undergraduate
    b. Masters
    c. PhD

8) Would you describe yourself as visually impaired? **Yes** **No** **No Answer**

POST TEST QUESTIONS

1) On a scale of 1-9, 1 being the lowest 9 being the highest, what was your level of cognitive load during the testing?

   1 2 3 4 5 6 7 8 9

2) On a scale of 1-5 (1 being ineffective and 5 being the most effective) how effective in instructing you about channel proteins was the *written material* provided?

   1 2 3 4 5

3) On a scale of 1-5 (1 being lowest and 5 being the highest) how excited were you about the material being presented?

   1 2 3 4 5

ONLY ANSWER IF YOU USED THE AR APPLICATION (#4 - #5)

4) On a scale of 1-5 (1 being ineffective and 5 being the most effective) how effective in instructing you about channel proteins was the *AR application* provided?

   1 2 3 4 5

5) Which mode of learning would you find most effective in a classroom setting after using the application?
   a. Only written/lectured material
   b. Only an AR application
   c. Written/lectured material in conjunction with an AR application
   d. Other (Please list):

6) Please leave any comments below that were not addressed in the questionnaire:

Appendix B: Written Material on Channel Proteins

An Overview of Channel Proteins and Their Functions

The membrane of a cell protects it from the outside environment and acts as a barrier, stopping molecules and particles from entering the cell. The membrane is hydrophobic, and made of phospholipids. Due to the structure of the cell membrane and its hydrophobic properties, many types of molecules and particles cannot cross from the outside of the cell into the inside. To solve this problem, certain types of proteins have evolved. These proteins are called *channel proteins*. A protein is a sequence of amino acids all bonded together. There are 20 amino acids found in nature, and they can form sequences that are thousands of units long. The order which the amino acids form this sequence will cause them to fold into a unique structure, with a specific and unique function. There are many categories of proteins, some that move molecules around (transport proteins), some that change the structure of molecules (enzymes), some that transfer phosphates from one molecule to another (kinases), and channel proteins among others.

Channel proteins are a type of a protein that fold into a channel that becomes embedded into the cell membrane. This channel traverses the phospholipid layers of the cell membrane, and connects the inside of the cell with the outside environment, and allows ions from the outside environment to travel through the channel into the cell, as shown in Figure 1 below.

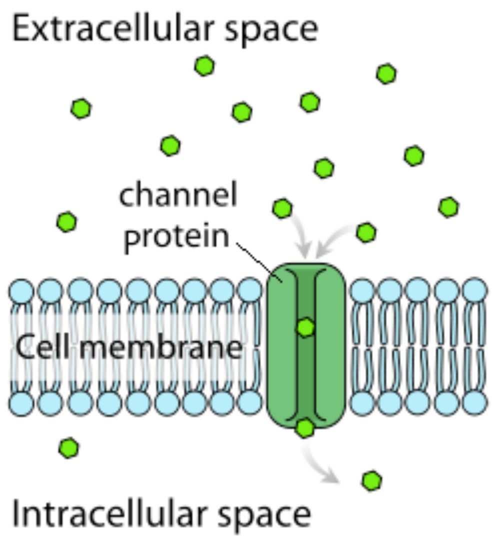

Figure 1 - Example of a channel protein (https://www.khanacademy.org/science/biology/membranes-and-transport/passive-transport/a/diffusion-and-passive-transport)

There are several varieties of channel proteins, each specific for certain types of ions or molecules being transported. The three major categories of channel proteins are:

1) Non-Gated Channels
2) Voltage Gated Channels
3) Ligand Gated Channels

Non-Gated channels, sometimes called *leakage channels*, remain open at all times, and a constant flow of ions in and out of several non-gated channels allows cells to maintain a correct balance of ions and charges. They are sometimes referred to as leakage channels because ions will "leak" out of the cell through them.

Voltage Gated ion channels are either open or closed depending on the voltage on the inside of the cell membrane close to where the protein is embedded. When the potential charge changes around the protein, it can cause a change in the structure of the protein that opens the channel up, allowing ions to flow through, or close the channel off, depending on which protein it is. Some voltage gated channels have a charged ion blocking the channel opening that gets pushed out when the voltage changes. An example of this is the NMDA receptor (a voltage gated channel that is important to memory and cognition), which has a magnesium ion in its channel that stops the flow in and out of the channel. This magnesium gets pushed out when the charge increases though, allowing ions to flow in and out until the charge once again decreases and the magnesium once again blocks the channel.

Ligand Gated ion channels are either open or closed depending on if the *ligand* is present. A *ligand* is a molecule that interacts with the protein at a specific location on the proteins structure, known as the proteins *active site*. The ligand gated channel will be in a closed position until the ligand comes and fits into the proteins active site, causing a change in the structure of the protein that opens it up to ion flow. There are many different types of ligand gated channels all with unique ligands. Some examples include the ligand gated channels found in our brains; there are multiple channels for each neurotransmitter in our brain, such as dopamine, serotonin, acetylcholine and many others. For each neurotransmitter (which acts as the ligand), there are several channel proteins associated with it. Ligand gated ion channels are also the focus of pharmaceutical research, as drugs that are developed will sometimes target a ligand gated ion channel.

Sources

Alberts B, Johnson A, Lewis J, et al. Molecular Biology of the Cell. 4th edition. New York: Garland Science; 2002. Principles of Membrane Transport. Available from: https://www.ncbi.nlm.nih.gov/books/NBK26815/

Cooper GM. The Cell: A Molecular Approach. 2nd edition. Sunderland (MA): Sinauer Associates; 2000. Transport of Small Molecules. Available from: https://www.ncbi.nlm.nih.gov/books/NBK9847/

Mesa, K. (2015). Essential Cell Biology. *The Yale Journal of Biology and Medicine*, *88*(1), 100–101.

Appendix C: Channel Protein Quiz

Post Test Assessment Quiz

Short Answer

1) What are proteins made of

2) Describe the general structure of a channel protein

3) Describe the function of a channel protein

4) Why do cells require a channel protein?

5) What is the difference between non-gated, voltage-gated, and ligand-gated proteins?

True or False

6) Channel proteins only allow certain molecules to flow in and out of it ___
7) A protein is essentially a 2D structure ___
8) Voltage Gated Ion Channels don't require a ligand ___
9) All protein channels allow any ion to flow in and out of it ___
10) Protein channels can be open or closed ___
11) Non-gated channels are closed most of the time ___

Multiple Choice

12) A channel that requires a specific drug to open it is a:

a. Voltage Gated Channel
b. Enzyme
c. Leaky Channel
d. Ligand Gated Channel

13) How many Amino Acids are there?

a. 16
b. 18
c. 20
d. 14

14) A Potassium Channel would allow what type of ion through?

a. Calcium
b. Potassium
c. Sodium
d. A and B

15) When a voltage gated channel opens, it could be because:

a. A change in charge near the protein has occurred
b. The proteins sequence of amino acids has change
c. A drug has activated it
d. A and C

16) Which is most correct about Non-Gated Channels?

a. They remain open to allow an exchange of ions most of the time in and out of the cell
b. They remain open at all times
c. They mostly remain open at all times
d. They remain open to allow constant exchange of ions in and out of the cell

Appendix D: Participant Consent Form

Consent Information Regarding the Study:
"Can Augmented Reality Increase Comprehension and Decrease Cognitive Load When Studying Protein Structure"

Investigator: Matthew Parrotta
Contact: mparrotta@laurentian.ca
Supervisor: Dr. Ratvinder Grewal (705.675.1151 ext 2351)

This study is attempting to understand if computer technologies, like augmented reality (AR), can be effectively used to increase retention and understanding in an educational perspective. The focus of the study is on understanding the function of channel proteins, and using an AR application to supplement the traditional written material. This research is important to understanding how modern technology and software can help future students learn more effectively, and to understand if this type of software has a place in the classroom.

What will be asked of you during the study includes:

- Filling out a pre and post test questionnaire, asking for some basic demographic information, as well as your level of knowledge in biology/biochemistry
- Reading an approximately two page write up on Channel Proteins
- Using an augmented reality application
- Completing a quiz on channel proteins

As a participant, you have the right to drop out of the study at any time. Any concerns participants have can be voiced before, during, or after the study at any time. You have the right to drop out of the study at anytime without giving reason for your dropping out.
During the study, all of the tests being performed will be explained and time for questions and concerns will be given to each participant. If participants want to drop out of the study, they simply will contact the investigator (Matthew Parrotta) via the provided email and inform him that they no longer want to participate. Similarly, if participants want to drop out during the actual scheduled study time, they just have to inform the investigator they wish to do so and they can without penalty at any point during the study. Participating in this study and/or dropping out will not have any effect on the participants academic standing, grades or future prospects with the university.

In the course of the study, certain personal information will be collected, including: age, gender and program of study. All information will be maintained using anonymous ID's for each participant, and the data will be stored in the Computer Human Interaction Laboratory (which is kept lock) in a locked cabinet. The data will be kept in this secured area until the completion of the study, after which it will be maintained in this secure location. No information will be shared with any third parties, and information will only be used for the writing and completion of the study only.

Concerns for participants may be:

- Reading comprehension from the provided written material
- If visually impaired, using the AR application may be difficult and/or cause some amount of eye strain (no more so than standard smartphone/tablet use)

Participants may contact the Research Ethics Board at any time if they have any concerns or questions regarding this study. Participants may contact an official not attached to the research team regarding possible issues or complaints about the research itself:

Research Ethics Officer
Laurentian University Research Office
Telephone: 705-675-1151 ext 3213, 2436 or toll free at 1-800-461-4030
Email ethics@laurentian.ca.

If all of the following above is acceptable to you as a participant, please leave you signature, date and email address below.

Signature: ______________________________

Email: ______________________________

Date: ______________________________

☐ Please check this box if you would like a copy of the results sent to your provided email once the study is complete

Appendix E: Participant Recruitment Letter/Classroom Recruitment Script

LaurentianUniversity
UniversitéLaurentienne

Hello,

My name is Matthew Parrotta and I am a second year master's student in Computational Sciences here at Laurentian University. I am here today to inform you of a study I am completing for my graduate thesis, and I am looking to recruit possible participants. My area of research is human computer interaction, more specifically, how software can be used for education. For my study, I am examining if augmented reality software can assist students in learning about channel proteins and their functions. Augmented reality is when your smartphone or tablet camera superimposes models into the 3D world. By participating in the study, you may have the opportunity to utilize unique software for biochemistry education. Participating in the study requires only one visit, where you will complete a pre-questionnaire, read a write up on channel proteins, potentially use the augmented reality software, write a short test and finish with a post-study questionnaire. The length of participating will be approximately half an hour.

If you are interested in the study, please contact me at mparrotta@laurentian.ca to schedule a time to participate. Participation is completely voluntary, and you may withdraw from the study at any time during the process without giving reason. If you have more question about the study or its protocols but don't necessarily want to participate, please feel free to contact me and I will gladly answer any questions or concerns you may have.

Thank you

Matthew Parrotta
Msc. Computational Sciences
mparrotta@laurentian.ca

Supervisor: Dr. Ratvinder Grewal (705.675.1151 ext 2351)

Appendix F: Laurentian Research Ethics Board Approval

LaurentianUniversity
UniversitéLaurentienne

APPROVAL FOR CONDUCTING RESEARCH INVOLVING HUMAN SUBJECTS
Research Ethics Board – Laurentian University

This letter confirms that the research project identified below has successfully passed the ethics review by the Laurentian University Research Ethics Board (REB). Your ethics approval date, other milestone dates, and any special conditions for your project are indicated below.

TYPE OF APPROVAL / New X / Modifications to project / Time extension	
Name of Principal Investigator and school/department	Matthew Parrotta, Computer Science, superviser, Ratvinder Grewal
Title of Project	Can Augmented Reality Increase Comprehension and Decrease Cognitive Load When Studying Protein Structure
REB file number	6016089
Date of original approval of project	December 14, 2018
Date of approval of project modifications or extension *(if applicable)*	
Final/Interim report due on: *(You may request an extension)*	December 14, 2019
Conditions placed on project	

During the course of your research, no deviations from, or changes to, the protocol, recruitment or consent forms may be initiated without prior written approval from the REB. If you wish to modify your research project, please refer to the Research Ethics website to complete the appropriate REB form.

All projects must submit a report to REB at least once per year. If involvement with human participants continues for longer than one year (e.g. you have not completed the objectives of the study and have not yet terminated contact with the participants, except for feedback of final results to participants), you must request an extension using the appropriate LU REB form. In all cases, please ensure that your research complies with Tri-Council Policy Statement (TCPS). Also please quote your REB file number on all future correspondence with the REB office.

Congratulations and best wishes in conducting your research.

Rosanna Langer

Rosanna Langer, PHD, Chair, *Laurentian University Research Ethics Board*