LearnDNA: An Interactive VR Application for Learning DNA Structure

Lakshmi Sharma
The University of Texas at Dallas
Richardson, TX, USA
Lakshmi.Sharma@utdallas.edu

Rong Jin
The University of Texas at Dallas
Richardson, TX, USA
Rong.Jin@utdallas.edu

Balakrishnan Prabhakaran
The University of Texas at Dallas
Richardson, TX, USA
bprabhakaran@utdallas.edu

Murry Gans
Eastfield College, Dallas County Community College District
Mesquite, TX, USA
mgans@dcccd.edu

ABSTRACT

Understanding complex concepts is known to be difficult and tedious. This complexity is very often due to lack of visual representation of abstract concepts, that cannot be easily observed. Representing these ideas in a visual Virtual Environment (VE) is a very important application of Virtual Reality (VR). This paper presents an immersive VR application for teaching students about one such complex concept of DNA structure. Building virtual environments that show the double helix structure of DNA and allowing students to interact with it, provides an illustrative and engaging experience. A crucial factor that determines usability of such systems is the correlation between actual concept and its virtual representation. Our virtual DNA structure is very similar to the actual structure, thus highlighting its complexity. This VE is built for Oculus Rift with simple clicker based manipulation and travel, to allow easy portability to other VR devices. The system also provides test based assessment to gauge students' understanding. The evaluation of this VE was carried out with the help from a group of Subject Matter Experts (SMEs). Through their feedback, we refined system design and subject content, as well as survey questionnaires. A subsequent user study was conducted in a local community college. Students were recruited from two biology classes and offered extra credit based on results recorded by this system. The study gave pre-test prior to virtual experiment, post-test following virtual experiment and survey session after post-test.
All SMEs felt that the application was useful for learning about DNA. Comparing the pre-test and post-test performance of the students, there was an average of 40% improvement in the scores, indicating that LearnDNA was able to facilitate learning the concepts. Most students also felt that the application was engaging and fun to use.

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CCS CONCEPTS

• **Human-centered computing → Virtual reality**; • **Applied computing → Interactive learning environments**;

KEYWORDS

Virtual Reality, education, DNA Structure

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1 INTRODUCTION

Since the introduction of head mounted virtual reality headsets, the number of VEs has been increasing at a rapid rate. The application of VR beyond gaming have been recognized, and it is being considered a revolutionary tool for education. As educational issues, especially that of attrition in science, technology, engineering, and mathematics (STEM), has become a major concern for the nation, many research projects, including [1–4] are being aimed towards integrating virtual laboratories in STEM education. These projects are aimed towards reducing the cost associated with STEM laboratories, and have been shown to be successful. Several collaborative systems have also been built to allow teachers to guide students without being physically present at the same location. Most of these projects create a virtual replica of physical laboratories.

One section of education that has not been explored much is, creating VEs to represent abstract concepts that are taught in schools but are difficult to be made available as experiments in physical laboratories. One possible reason for attrition in STEM education is due to the complex and tedious abstract concepts, which are perceived as challenging topics by students. Such concepts and difficult to dynamically visualize or be properly represented as structures in physical class or laboratories. Virtual learning environment, such as virtual laboratories, in which students convert their theoretical knowledge into practical knowledge by conducting experiments [1, 5] or transform knowledge of static images into 3D structures [6], can address this lack. Another concern with VR systems built for education is lack of structure. For integrating VR systems into schools and educational institutes successfully, the systems should be designed in a way that makes it easy for inexperienced users to start using it. This paper aims at addressing these two issues.

LearnDNA creates a VE for teaching students about the DNA structure in a 3D virtual environment. The DNA structure cannot be physically observed in school laboratories, and thus, is taught using traditional text and image based methods. This system also creates a design that can guide unaccustomed users about using the system before introducing the DNA structure; it also provides an automatic testing module to gauge the student's understanding. The performance of users is logged by the system for grading purposes. Another prominent issue addressed by LearnDNA is to design systems that are portable to various VR devices. An iterative approach was taken for developing LearnDNA.

This paper contributes by sharing experiences with:

1. Building 3D DNA models and interactive components for such abstract concepts

2. Building a complete system that can be used in STEM laboratories for both teaching and evaluating students.

3. Using iterative development methods and collaborating with Subject Matter Experts (SME) for building better systems

The user experience studies conducted after each iteration show the usefulness of such a system and the drastic improvement in test performance of some students who learn better in a visual environment. LearnDNA is being integrated into biology class at local community college to provide better virtual laboratories.

2 RELATED WORK

There have been some efforts in incorporating virtual laboratories for abstract concepts in education like [7]. This paper is based on building VEs suitable for engineering students, where they can learn about topics in a VR scene containing the recommended learning materials for that topic. Another work, [8] has developed 3D models for VR, that show visualizations of Molecular Biology concepts. While these and other such works have made significant contributions to education in VR, most of them are mainly aimed at providing a static VEs without interaction capabilities. Some VR tools like [9] show 3D models of DNA, but have limited functionality and are not aimed at providing a pedagogical education system. Some other work like [10] are aimed towards doing research with much complex concepts. [10] presents a molecular mechanics study in new nanorobotic structures using molecular dynamics. While this can be very useful for research purposes, its application as an educational tool for community college students may be very limited.

An older paper that addresses several of the issues being discussed in this paper is [11]. This paper studies how VR aids complex conceptual learning. The conclusions of this paper show the importance of having an iterative design for such VEs. This paper also talks about design trade-offs required building a useful system. However, this paper is based on older VR systems with restrictive abilities and higher costs. With the introduction of low cost VR devices that are lighter and have better interaction tools, the usability of such applications has changed.

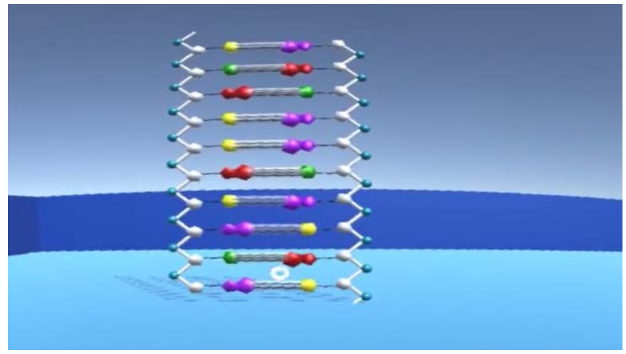


Figure 1: Initial Prototype.

One recently developed prototype for interactive visualization of DNA and RNA is CSynth [12]. It provides an engaging way to explore and understand the complex structure of the genome in 3D. This application has been designed keeping the needs of researchers and scientists in mind. While LearnDNA is focused more on developing a usable educational tool for students who are beginning to enter the STEM field. Although there is an overlap between these two applications' subject matter, their motivations are different and therefore the overall structure of these applications and research associated with them will be divergent.

3 ITERATIVE DESIGN

LearnDNA has been designed using an iterative and incremental development model. Iterative development methods have been used for building educational games [13] and have shown superior results. When building visual systems for abstract concepts, an iterative design become even more important. A collaboration between development researchers and SMEs has been used to develop an incrementally improving educational system for teaching DNA. LearnDNA has gone through three major iterations, each of which has been discussed in the following sections along with specific design details.

3.1 First Iteration

The motivation for developing an educational tool for learning about DNA, was an absence of good visualizations that allowed students to interact, and engaged them to keep learning. To understand the requirements of such a system, an initial prototype was built. This prototype, shown in Figure 1, included basic 3D models of nucleotides. It also provided interaction techniques for viewing information about nucleotide bases and for placing base pairs on one side of a DNA strand. The system required a Head Mounted Display (HMD) with at least 3 degrees of freedom (DOF) that provide head rotations, and a clicker input. The prototype showcased the basic features that provided an interactive 3D environment. It was then shown to SMEs and their feedback was used to improve the VE with the end goal of making it a complete pedagogical system. The feedback collected at the end of this iteration was mostly qualitative.

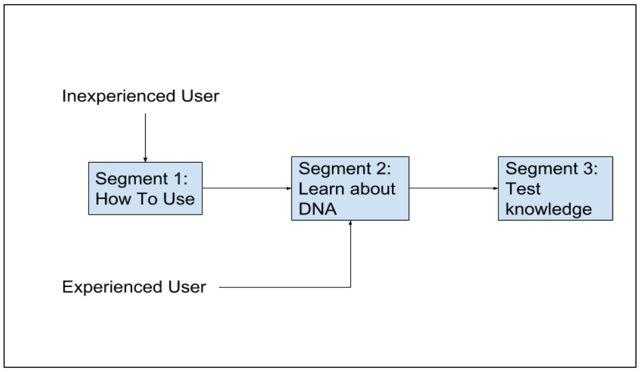


Figure 2: System Flow.

3.1.1 Evaluation and Feedback. Following key points were recognized after performing the first evaluation:

1. Providing better 3D environment to improve immersive quality
2. Show 3D structure of DNA and information about various components
3. The functionality shown in prototype should be included as a tool to test students
4. System should be portable to other VR devices (the first version was built for Google Cardboard)
5. The instructions that were given to SMEs, when they tried it out for the first time, should be available inside the environment.

3.2 Second Iteration

The feedback on first iteration was used to design and build a more complete environment. A new system design was formulated such that it could be used on any VR device having 3 DOFs. This makes it possible to easily port this VE to other devices without losing any functionality. Devices such as GearVR and Google Cardboard are more affordable and have already been adopted by some schools for viewing non-interactive environments. Two key issues that affect quality of experience in these cheaper devices are: (1) absence of translational DOF which makes movement in VE difficult, and (2) complexity of 3D models which affects the application's performance. This system was designed keeping both these factors in mind. Travel techniques that are not dependent on 6DOFs were used and the 3D structure was built using minimalistic 3D models, but with enough details to have good correlation between actual structure and virtual representation. As the main aim of this paper was to study the usefulness of VR in education for abstract concepts, Oculus Rift version was used to perform user studies.

The second iteration design consisted of three segments which addresses the following requirements:

1. Teaching student HOW to use this system,
2. Teaching student about DNA,
3. Evaluating what student has learnt.

Using these three segments, students could be guided gradually from beginning to use the system, to learning about DNA, and finally, to giving tests to check their understanding. Figure 2 shows that the first step is required for only inexperienced users. Others who have used the environment previously do not need to use the

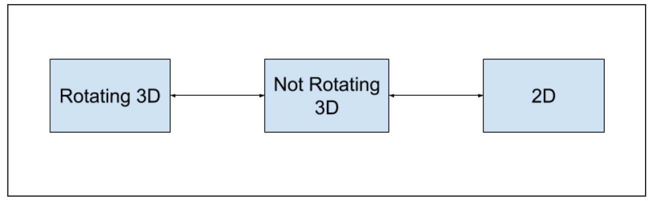
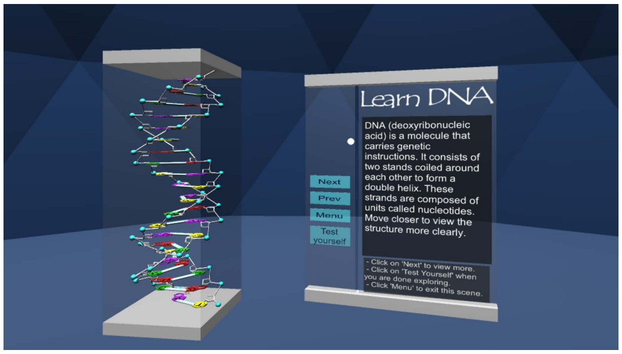


Figure 3: Viewable states of DNA in LearnDNA.

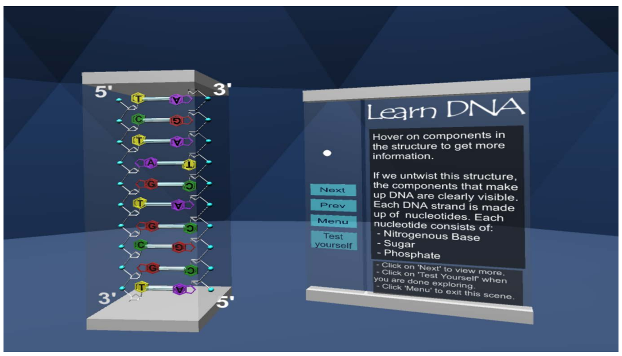
first segment. The following subsections discuss each segment in more detail.

3.2.1 Segment 1: How to Use. When a student enters a VE, the first step is to familiarize the student with their environment. This segment guides the user through a series of tasks that will be useful for manipulation and travel. Clicking, traveling and hovering are some of the tasks that a student can perform to be able to interact with components. Without these basic skills, the student would not be sufficiently equipped with the knowledge they need to learn from this VE efficiently. For example, if users don't know how to hover over a component in VR, they cannot get information about various sub components of DNA. Therefore, it is important to have a guiding segment to reduce the dependency of a student on teacher when they begin to use VR. This is also important as VR has been introduced to the field of education only recently. Most students might not have used VR before and may not intuitive begin using it. This type of initial guidance is also seen in most games and software tools. Students who are not familiar with VR can first go through it and then dive into the actual learning environment. Three main techniques used in this game are (1) clicking using handheld input clicker or button in mobile based VR devices, (2) hover on components for 2 seconds to view more information about them, and (3) walking around in the virtual world by clicking on the floor. The third technique is the most difficult one to get used to for most users as it is not very intuitive. But seeing that moving around in the scene is a necessity to allow students to get closer to the DNA structure, a technique that would be suitable for any VR device has been implemented. In this technique, users look at the floor position where they want to go and click to move to that position. As mentioned before, this kind of travel is not very intuitive. Therefore, it is very important for unaccustomed users to go through this segment.

3.2.2 Segment 2: Learn about DNA. Once students are familiar with the tool after using segment 1, they can then proceed to learning about DNA. In this segment, students view a rotating 3D DNA structure and information about it on a board placed next to the DNA strands. The DNA structure is the most critical component of this VE. The aim of creating this system was to study how students can learn about an abstract concept, which cannot be viewed in school laboratories, in a VR setup. This required the virtual DNA structure to be as close to the conceptual understanding of DNA. DNA has a double helix structure where two strands of nucleotides are connected using hydrogen bonds. The double helix also has major and minor grooves caused by the angle formed between two base pairs when they are connected. Although DNA has multiple



(a) 3D structure of DNA.



(b) 2D structure of DNA.

Figure 4: Structure of DNA.

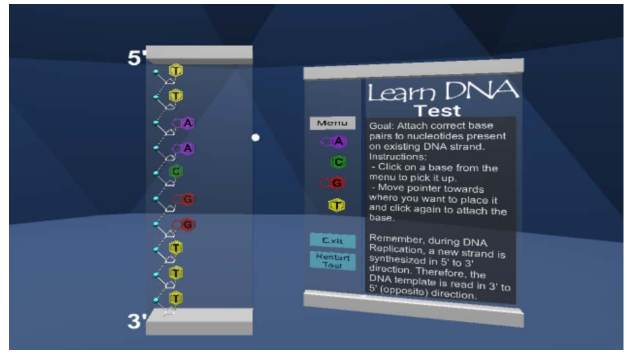


Figure 5: Test Scene.

forms, the structure shown in this VE is based on the most common DNA form. The components that a DNA molecule is made up of are phosphate groups, sugar molecules and nucleotides connected with hydrogen bonds. Nucleotides can be of 4 types: Adenine (A), Thymine (T), Guanine (G) and Cytosine (C). Hydrogen bonds exist between A-T and C-G only. No other combinations can be formed. When a student enters this segment new DNA strands are created from randomly selected bases, and double helix is formed on the fly using a formula for calculating positions of the bases on a helix. The phosphate, sugar molecules and bonds are placed in relation to the base pairs. The 3D models of each sub component are close representation of actual molecules. For example, the sugar group, is a 5-carbon molecule having a complex 3D pentagon shape. If these models are not created properly, the resulting DNA will not be similar to actual DNA.

The learning segment shows DNA in various states so that students can better understand it. Figure 3 shows all the states in which DNA is shown. Students can use 'next' and 'prev' buttons to switch between states. Additional information about DNA is shown on the board in every state. The first state shows a rotating 3D DNA so that students can view it from all angles. The next state also shows a 3D DNA, but without rotation. The next state is a 2D structure that shows how DNA would appear if it was unwound. This unwound state has less nucleotides than the 3D state to accommodate for visible space. These 3D and 2D states are shown in Figure 4. Each component of the DNA is interactive. Students can hover over each component to see more information about it. A temporary screen appears in front of the user for the duration he/she is hovering over a component. This screen shows information about the component and disappears when user stops hovering. User can also travel in the virtual scene using techniques mentioned in Segment 2 to move closer to the DNA and observe it closely. A 'Test yourself' option is available in this segment to allow users to move to Segment 3.

3.2.3 Segment 3: Test knowledge. The last segment tests the student's knowledge based on what was learnt in Segment 2. A single strand of DNA is visible in 3D space. This strand is randomly created when user enters this segment. A list of possible base pairs is shown on the board along with instructions about goals of the test. Two things are tested in this segment. The first is, on which side i.e. either 3' or 5' does DNA replication takes place. As the visible strands run from 5' to 3' (top to bottom), the replication process takes place from bottom end. Therefore, the student should place a base pair nucleotide at the bottom end first and move up from there. The second point of test is to check if student understands base pairs. As base pairs exist as A-T and G-C the appropriate base should be picked from menu and placed at the correct location. A base can be picked up by clicking on it in menu. An appropriate message is displayed once user clicks again to place the nucleotide base. A message showing 'Wrong' is shown if one of the following takes place:

(1) Base pair is not places from the bottom end
(2) Wrong nucleotide base is being placed
(3) Base is being placed too far away from its pair

Student may exit or restart test at any point. When test is restarted a new random strand is created and student needs to start placing base pairs again from the bottom end. If student exits, he/she is taken back to main menu. Figure 5 shows the test scene.

3.2.4 Evaluation and Feedback. The second evaluation was performed as a user study, which was carried out with a group of 8 SMEs consisting of 2 teachers and 6 students who were already familiar with the subject matter. This group consisted on 5 males and 3 females. A survey consisting of both quantitative and qualitative questions was filled out by the SMEs. The results of this have been shown in Figure 6 which is a box plot diagram showing results of a 7-point Likert-type scale from -3 to 3. The list of questions associated with this box plot is given in Table 1. The first set of questions

Table 1: Survey Questions

Questions
Usability
Q1. It was easy to learn how to use the system (using 'How to use' option)
Q2. I felt comfortable using the system
Q3. I felt comfortable interacting with objects in the scene
Usefulness
Q4. The system was useful for learning about DNA
Q5. I was able to understand the DNA structure better because of its 3D representation
Q6. The test was easy to take after viewing the 3D structure
Immersive Quality
Q7. The system was immersive
Q8. The system was engaging and fun to use
Q9. I would recommend this system to others

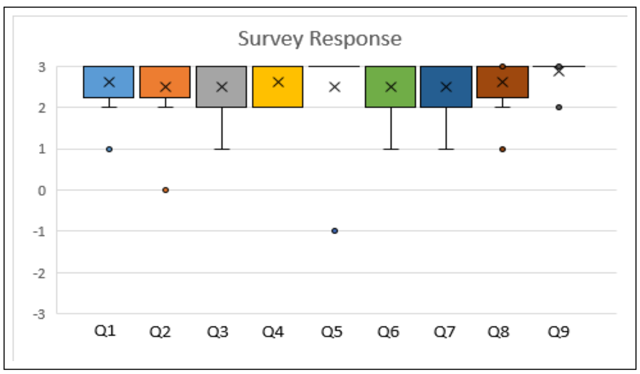


Figure 6: SME survey response, based on Table 1 Questions responses with a 7-point Likert type score between -3 and 3.

are based on usability of the system, the second set is based on usefulness, while the third set is based on immersive quality. An analysis of Figure 6 shows that all questions received very high scores in both maximum value as well as third quartile value. While the first quartile value remained close to median, a few outliers were also seen in some of the questions. Overall, the graph shows a high level of satisfaction and very little deviation in opinion on most questions. All SMEs appreciated our work and provided some insights about their experiences in the VE. One SME gave the following comment- "I'm a visual learner, so I greatly appreciate the ability to learn through visual interaction. The use of the headset limits distractions from the environment, but background noise creates its own distraction. Adding optional audio instructions with the use of noise cancelling headphones as an option might help minimize distractions.".

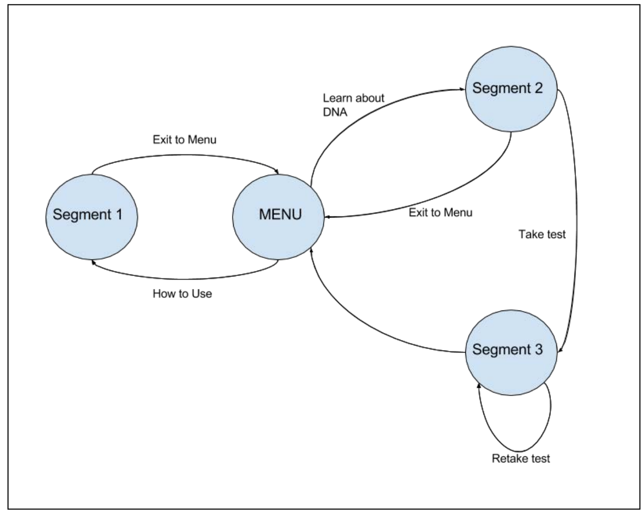


Figure 7: System state diagram.

3.3 Third Iteration

After performing evaluation and getting feedback on the second iteration it was recognized that the results of test should be stored for evaluating student's performance. The third iteration proposed the addition of a data logging section that stores user data and logs information about user's performance during test. As mentioned before the test evaluates two key factors, direction of placement and correct base pairs. Both these factors are recorded using a simple method to check the number of wrong placements before the first correct placement for every base pair. The number of wrong placements for the first base can signify the student's understanding of direction of placement and subsequent placements show base pair knowledge. These scores along with the base strand are logged for scoring and future use. The time taken by the student in every segment can also be recorded to evaluate the VE's effectiveness.

3.3.1 Evaluation and Feedback. The evaluation of this segment was done through a user study carried out at one of the campuses of Dallas County Community College District (DCCCD) - Eastfield College. This study consisted of 20 participants, 16 students and 4 others. The experimental setup and quality of experience analysis for this segment will be discussed further in section 5.

4 LearnDNA IMPLEMENTATION DETAILS

LearnDNA application has been built using Unity Game Engine with Virtual Reality Support. Oculus VR SDK needs to be selected while building for Oculus Rift. Google VR SDK is also being used in this application for enabling relevant Event System and providing Reticle Pointer control. Oculus SDK is required as Oculus Rift button clicks are not directly recognized by Unity and need to be detected using available scripts. Building for a phone based VR device requires Android SDK and JDK 1.8. VR for Android requires an API level 21 or above. For running on Oculus Rift the minimum computer system requirements in terms of RAM, GPU, ports etc. should be met. The 3D models used in this application have been

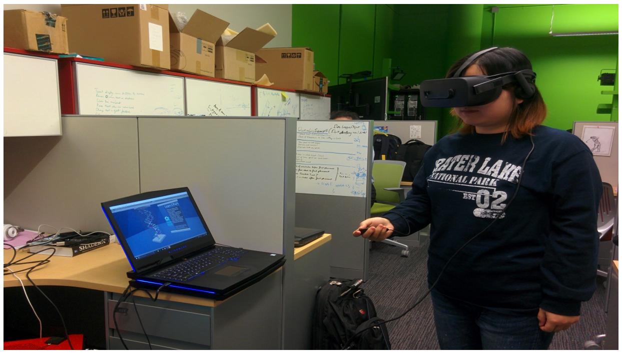
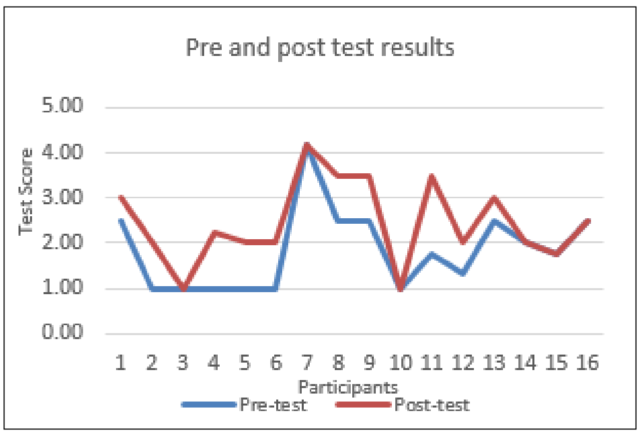
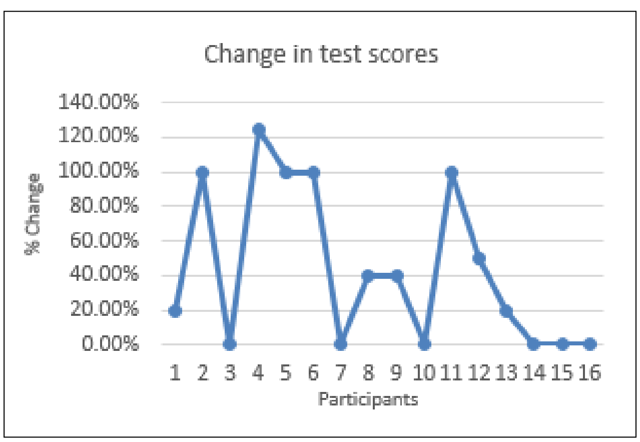


Figure 8: A user playing LearnDNA.



(a) Pre and post test scores.



(b) Change in pre vs post test score.

Figure 9: Test scores.

built using Blender. Various prefabs have been created to facilitate in building DNA structure on the fly.

The application begins with taking user information to record with logs. It then opens the 3D Menu scene at which point user should put on the headset. User can navigate from Menu to Segment 1 (How to Use) scene and Segment 2 (Play) scene. Segment 3 can be

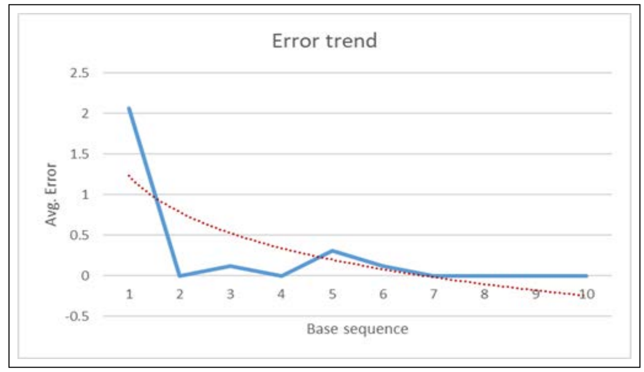


Figure 10: Error trend in scores recorded by Segment 3 of VE.

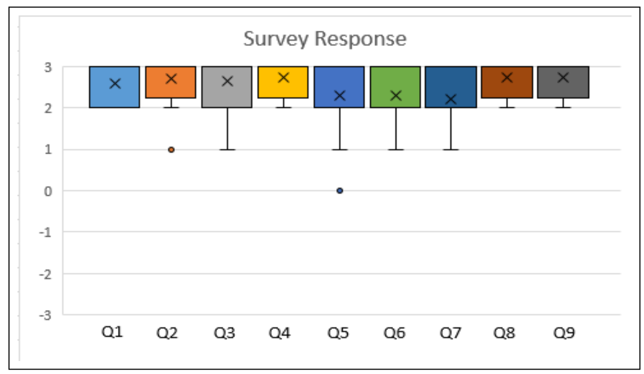


Figure 11: Survey response after third iteration, based on Table 1 Questions responses with a 7-point Likert type score between -3 and 3.

reached after entering Segment 2. The given test base pairs as well the list of number of errors are stored in database when user exists Segment 3. This is also explained in Figure 7 in the form of state diagram. Segment 3 logs user's test performance. Figure 8 shows the system being used. LearnDNA can be used in educational institutes for providing practical sessions while teaching about DNA. The scores recorded can be used for grading purposes.

5 EXPERIMENTAL SETUP & USER EXPERIENCE STUDY

The third iteration of LearnDNA was evaluated and used for the purposes of grading students. Both the second and third iterations' user study was done using Oculus Rift devices to provide best visual feedback quality. The first section here explains experimental setup; the second section gives analysis of results of a user study designed specifically to understand the usefulness of LearnDNA; lastly, the third section gives a detailed analysis of User Experience study.

5.1 Experiment Setup

The second segment was carried out using two separate setups, each consisting of one Oculus Rift and one computer. For running

Oculus, computers with good graphics cards, 16GB RAM and i7 processors were used. One Oculus has a clicker input while the other has a touch controller, with same functionality. A total of 20 participants performed user study in this iteration out of which 16 were students of Eastfield College. These 16 students also participated in a specialized user study designed for evaluating pre-experiment and post-experiment knowledge. The students first took a written pre-test, after which then used the VE system. After participating in the experiment, they filled out a survey and again gave a post-test. All the participants were given the same survey questionnaire. The pre-test and post-test results were graded on a 0-5 pointer system. The students also gave another test within VE in Segment 3. Scores for this test are also recorded by the system. Students were graded based on the VE based test's scores.

5.2 Analysis of Tests

The pre-test and post-test submitted by the students were graded by an SME. The questions asked in these tests are available in Appendix A. Figure 9 shows the results as well as percentage change in scores. These results show a significant improvement in subject matter knowledge. While all changes in performance were positive, 5 students showed a quantum improvement of 100 âĂŞ 120%. More than 50% of students that showed no improvement already had an above average score. Overall, a 40% increase in scores was noted.

The VE based test recorded the number of mistakes made by a user before placing the correct base pair in correct location. This has been explained in section 3.3. The number of errors was recorded for every base, for every student. An average error score was recorded for every base pair. Figure 10 shows the average errors recorded. This graph shows a high error rate for the first base pair signifying that most students had difficulty placing the first base. This in turn signifies that most students did not understand directionality of DNA stand. The average error scores also show a trend of reducing errors right after placing the first base. This signifies that most students understood the A-T and G-C base pairing correctly.

5.3 User Experience Study

All users were asked to fill out a survey questionnaire for the application. Among the 20 participants, 9 were male and 11 were female. While all participants were above 18 years of age, 16 were students and 4 were teachers. The analysis of the results was done using the same methods as that in second iteration. The box plot diagram for the same survey questions, but for third iteration, is shown in Figure 11. This study with mostly students showed very similar results as second iteration, but with even fewer outliers. There was a prominent level of appreciation for the system by the students. The analysis of this survey shows us that students found it to be useful, usable as well as immersive and fun.

Feedback from most participants was positive and almost everyone felt that LearnDNA could be a useful tool in teaching about DNA. One of the students gave the following comment - "I loved how easily I got to understand more about the structure of DNA. Technology like this can change worlds! I am a visual learner and having this in my classroom to understand the structure of DNA, its bases and structure would of definitely gave an A on a biology exam I had last week.". Another student gave the comment - "I like that the DNA structure was rotating in a 360 degree. I think they should keep it to show movement and draw in attention.". These comments show that having a 3D visual representation of a concept that cannot be otherwise observed by students in a laboratory provided a valuable tool for students who are visual learners. Some participants also gave useful insight about how the system could be improved.

6 CONCLUSION & FUTURE WORK

LearnDNA is an interactive VR environment to teach students about DNA structure. This system provides a useful design for creating complete VR environments that guide students about using this VE, providing interactive 3D structure to teach about the subject and finally taking tests and logging results to gauge user's understanding. LearnDNA shows that VEs can be an effective and engaging tool to teach students about concepts that cannot be viewed in school laboratories. As only 3 DOF of VR headset, along with a click input, is used, this setup is easily transferable to any VR headset. The 3D structure's interactive nature encourages students to explore and discover information which helps in improving retention [14]. LearnDNA shows the efficacy of VEs in education and can help retain more students in STEM fields. Further user study, comparing VR educational system and traditional educational system such as text or models, can be performed to correctly gauge the system's usefulness. Such a study could not only address comparison of the two modes of education in terms of ease of learning, but also compare change in students' interest in the STEM field after experiencing a more engaging mode of education.

The detailed discussion of iterative development is a major contribution of this paper. It shows both quantitative and qualitative improvement with each iteration. Such a model can also be adopted by other researchers working in educational and training research and development.

Feedback received after third iteration has given us many areas of improvement that will make the system more useable and useful. The major areas that can be worked on in future include: 1. Building a collaborative system and 2. Improving travel technique and 3. Integrating audio instructions. For building a collaborative system, many of the approaches used in [1] can be integrated to allow teachers to remotely monitor a student's 3D world interactions as well as view recorded videos of the same. The travel technique used in this system is useable on any VR device, but it is not very intuitive or easy to use. Another way to allow travel is to use a Leap Motion device and take gesture control input to allow navigation in a scene [15]. A virtual travel navigation dock can be placed inside the scene that will take gesture input to determine direction and speed of user's movement. As Leap Motion can also be used along with any VR device, using 6 DOF of a VR headset can be avoided. This can highly improve the overall usability of the system as easy travel gives a higher level to freedom in any VE. Lastly, a common issue with both textbook based learning and LearnDNA is the requirement to read information off a paper or screen. Providing audio instructions in VEs has been shown to be more effective [16]. Most of the information available in this system can be converted to audio instructions to build a more immersive and functional environment.

A APPENDIX

Pre-test and Post-test questions:

1. Name or give the single-letter abbreviation for the bases that are found in a DNA molecule.
2. In addition to the bases, what other molecules are found in a DNA molecule?
3. How do the bases from one strand of DNA connect to the bases from the other strand? Be as specific as possible.
4. What are the ends of a single strand of DNA called?
5. During DNA synthesis, one strand serves as the template for the formation of the complementary strand. What rules apply to DNA synthesis?

Post-test included an additional section for comments or suggestions.

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