Journal of Universal Computer Science, vol. 26, no. 8 (2020), 929-946
submitted: 14/1/2020, accepted: 8/7/2020, appeared: 28/8/2020

Influence of Virtual Reality on High School Students' Conceptions of Cells

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Abstract: Cells are central to the study of biology, yet many learners have difficulties understanding the abstract yet fundamental foundation of life. Research suggests that students' conceptions of cells are reinforced by current biology learning materials, which represent cells as two dimensional, highly ordered, and mostly empty. These models also inaccurately represent the number, location, and size of organelles. We examine the effect of an inquiry-based three-dimensional virtual reality (VR) game on high school students' mental models of cells. Students reported that the game was more interactive and engaging than traditional ways of learning about cells and attributed an improved understanding of cells to their game experience. Students' post drawings of cells depicted more types of organelles, increased density of organelles, and additional complexity than their pretest drawings, indicating a movement towards more accurate mental models of cells. However, students' scores did not improve on their factual knowledge about cells between the pretest and the post-game biology assessments. We discuss the implications of incorporating game-based approaches and new technologies such as VR into biology education.

Keywords: virtual reality, cellular biology, high school, STEM education
Categories: L.1.1, L.2.3, L.3.0, L.3.6, L.5.1

1 Introduction

Understanding cells is central to the study of biology [NGSS, 2013], yet the visualizations available to teach students vastly oversimplify the densely packed, dynamic environment of the cell. Research on students' conceptions of cells has shown that students think cells are two dimensional [Vijapurkar et al, 2014] and that all types of cells are circular, and all cells are similar size [Vlaardingerbroek, Taylor & Bale, 2016]. Additionally, students believe cells are primarily empty and that all organelles within the cell are the same relative size [Vlaardingerbroek, Taylor & Bale, 2014].

These conceptions are reinforced by current biology learning materials, which depict cells as two dimensional, highly ordered, and mostly empty, and inaccurately represent the number, location, and size of organelles [Tibell & Rundgren, 2010].

Educators need ways to include more complex representations of cells so that teachers and students may develop more sophisticated ideas about cells [Celiker, 2013]. One way to address this issue is by incorporating new types of visualizations into biology education, Research suggests that complex models improve students' conceptions about cells and their motivation to learn biology [Host et al., 2013]. This study explores how an immersive virtual reality (VR) game can impact students' conceptions of cells. This article will summarize existing research on students' understandings of cells, explore how external representations have been used in biology learning, and share a study about a VR learning game designed to help students develop authentic views of cells.

1.1 Students' ideas about cells

Understanding the nature of cells is essential to biology learning. "Structure and Function" (LS1A), which emphasizes the role of cells and cell processes in the lives of organisms, is a core component of the Next Generation Science Standards (NGSS). Cells, however, are complex, diverse, and usually invisible to the naked eye. Research has shown that students have difficulty considering the relative size of microscopic objects [Tretter, Jones & Minogue, 2006], especially those that cannot be measured directly [Jones, Taylor & Broadwell, 2009]. Students new to biology find cells challenging to mentally conceive and can be led to believe a number of different misconceptions over the course of the curriculum.

In sculpting students' conceptions of cells, teachers commonly resort to real-world analogies that are meant to make these microscopic organisms more easily construed [Tsatsarelis et al., 2000]. Teaching tactics like anthropomorphization, using "human" metaphors for non-human objects, are also common. In order to mitigate cognitive load for beginners, teachers regularly use visuals (textbook diagrams, microscope slides, etc.) that help simplify cells to their barest components. Analogies and simplified visuals, however well-intended, can be misleading. Inexperienced students may accept these images as fact and believe that cells are two dimensional, perfectly round, share the same general size and shape regardless of function, and contain very few organelles or other internal structures [Flores et al, 2003; Vlaardingerbroek, Taylor, & Bale, 2014]. Anthropomorphization, furthermore, can lead students to believe that cells and cell structures have personal agency and are consciously in charge of their own functions [Tibell and Rundgren 2010; Tamir and Zohar, 1991].

Due to these preconceptions of cells as empty, static objects, students may face difficulty in connecting cell structure to function [Tan & Waugh, 2013]. Students might understand individual biological functions of cells, but not how these functions are interconnected in a greater system [Dreyfus & Jungwirth, 1988; Lewis & Wood-Robinson, 2000]. These misconceptions and gaps of understanding may be carried beyond schooling and into adulthood - educators, too, are vulnerable to believing and expressing fallacies. Research shows that even incoming science teachers have trouble identifying the shape and frequency of fundamental organelles within animal and plant cells [Çeliker, 2013].

1.2 Virtual Reality

One method of visualizing biological conceptions is through virtual reality (VR). VR uses technology to provide visual, audio, and haptic information to the user, creating an immersive visualization [Goddard et al., 2018]. With a decrease in cost and increase in availability of equipment, VR applications are gradually gaining a wider audience. VR training programs are already being utilized in medicine [Li, Yu, Shi et al., 2017], the military, and aviation [Slater & Sanchez-Vives, 2016], and new applications are being developed for training in fields such as architecture [Sopher, Gewirtzman & Kalay, 2019]. Companies are using VR modeling not only for training but also for research and collaboration, including collaborative molecular modeling [Kingsley et al., 2019] and computational chemistry [Salvatori et al., 2016]. VR is especially well suited to creating a sense of presence, the feeling of being in the virtual space [Slater & Sanchez-Vives, 2016], and in allowing users to experience embodied cognition by using their entire body to learn [Goldberg-Johnson, 2018].

1.2.1 Presence

Presence describes the psychological feeling of being in the virtual environment, while immersion, such as a head mounted display (HMD) is the technology that enables the psychological feeling [Slater & Sanchez-Vives, 2016; Shu et al., 2019]. The effect of presence and immersion can be powerful. Users in a virtual environment at the top of a cliff will refuse to step off the edge, even knowing that it is a simulation. Presence is enhanced when the interaction between the user and the environment is seamless and natural and is reduced when the technology impedes the experience [Riva & Watersworth, 2013]. Presence affects learning by creating a more salient learning experience that can improve the ability for the learner to absorb and retain information [Minocha, Tudor & Tilling, 2017].

1.2.2 Interactivity

Another affordance of VR is interactivity [Goldberg-Johnson, 2018]. Immersion in the virtual environment allows the user to engage with the material with their entire body, tapping into the concept of embodied learning [Stolz, 2015]. VR experiences have a range of interactivity. In some cases, the user can only move forward and backward and cannot interact with the information in the virtual world; in other experiences users can move freely and engage with the virtual world through hand controllers or specially designed gloves [Thompson, Kaser, & Griijvala, 2019]. An increase in interaction with the virtual world enables learners to experience embodied cognition, where students use their entire body to learn [Weisberg & Newcombe, 2017]. Thus, the level of interactivity impacts the learning experience.

1.3 VR and learning in biology

A number of VR applications have been developed for biology education. Peppy is a VR environment that allows users to understand protein structure by manipulating virtual protein structures (https://www.biorxiv.org/content/10.1101/723155v2). Users can take 360 virtual tours through human cells in Cellscape: VR Biology (https://www.tdwscience.com/cellscape-360o-vr) and Journey to the Center of a Cell (https://artdesign.unsw.edu.au/3DVAL). In The Body VR learners explore the body by travelling through the bloodstream and different parts of the body (https://store.steampowered.com/app/451980/The_Body_VR_Journey_Inside_a_Cell/) InCell is an action game where players battle viruses in VR (https://luden.io/incell/). Research on learning in VR has also grown steadily. [Johnson et al., 2017]'s comparison of a VR based cell exploration and a traditional lecture style presentation, showed that students who viewed the VR simulation were better able to explain the process of how a particle could be internalized in a cell than students who did not view the simulation. Parong and Mayer [2018] found that students learned more about cells through a slide deck rather than the VR based In Cell: Journey Inside A Cell, but the VR version was more motivating to students. Furthermore, text prompts helped students learn more from both VR and non-VR implementations. Providing students with background information before the experience can aid learning. Mayer, Omdahl and Makransky [2019] compared the effect of pretraining students with a diagram of a cell before a VR and non-VR video. Pretraining resulted in a statistically significant increase in recall only for the VR group and had no effect on the video group.

Studies have also explored VR in classroom settings. Tan and Waugh [2016] described a molecular biology unit where students used stereoscopic glasses to view DNA, proteins, and molecules in a high school class in Singapore. Students reported that the VR lessons made molecular biology less intimidating and abstract, and improved their ability to connect biological terms to conceptual processes. However, the improvement in pre and post assessment was statistically significant for male students but not female students. Ibarra-Herrera et al [2019] developed a game-based VR Bio3D app to help engineering students learn the central dogma (protein synthesis through DNA and RNA). The app incorporated two approaches to teaching the material, a storytelling approach that provided a narrative around a specific topic and a game-based approach. Twelve engineering students evaluated the game according to motivation, usability, and knowledge. They found that the game-based approach was more motivating than a storytelling approach. Barko and Sadler [2013] used the video game Mission Biotech to introduce students to biotechnology. In the game, students learn fundamental concepts of biotechnology and biotechnology related processes through becoming a researcher in a virtual laboratory. They studied 90 students in three classes, two classes implemented Mission Biotech in one class period, the other group implemented Mission Biotech in two class periods over a two-week period. Students in two groups had significantly higher scores on the post test, but the authors found no change in students' attitudes towards science and science careers.

2 Theoretical framework

2.1 Students' conceptions and mental models

Visualizations enable students to make the conceptual leap to a microscopic scale through prompting mental models of cellular processes. Mental models are defined as "ideas that represent the construction of imaginative understanding and visualization in the minds of students used to describe phenomena" [Majid & Suyono, 2018, p. 244]. Mental models include images and properties and rules of procedures, can be contradictory and incomplete, and do not have clear boundaries [Redish, 1994]. As a result, students can be confused about one topic, but have a good understanding of a related topic. Misconceptions represent a mismatch between students' existing ideas and the models they encounter. Researchers have devised ways to track how students develop these ideas [Ifentalter, Masducki & Seel, 2011]. Mental models can be externalized as conceptual models through drawings and discussions of the components of a system [Dauer et al., 2019]. Drawings show many ideas simultaneously and can aid educators in eliciting student's ideas by "making thinking visible", revealing students' patterns of thinking about a topic [Kose, 2008].

Studies have identified how conceptions about cells and cellular processes can result in incomplete mental models. Dikmenli [2010] investigated preservice teachers' misconceptions of cell division by having them draw the processes of meiosis and mitosis. Most preservice teachers' drawings were partially correct but included misconceptions, showing that they were able to recall some aspects of the processes but could not assemble them into an accurate mental model. Celiker [2015] also evaluated preservice teachers' drawings and writing responses, finding that a majority of preservice teachers' drawings did not accurately represent the cell. Dauer, Bergan-Roller, & King [2019] investigated students' changes in mental models through their drawings of concept maps before and after a lesson about a gene regulatory system. They found that students' initial models were general and incomplete; after the lesson, students' maps increased in the number of structures and relationships between those structures in the model.

2.2 Selective attention

Another theoretical framework to consider in this study is the concept of selective attention. Selective attention is the specific and conscious focus on particular information that is relevant to one's interest [Witmer & Singer, 1993, Wirth et al., 2007]. Users might focus their attention to a stimulus because it is interesting to them or the medium makes them direct their attention [Wirth et al., 2007]. Individuals who have higher attention on tasks or stimuli in VR will be more involved in the VR environment [Witmer & Singer, 1993]. In VR learning environments, the tasks play a critical role in attracting individuals' attention [Bigne et al., 2018]. The specific goals in games help direct players' attention to parts of the virtual world and provide a reason to activate that knowledge while playing [Merchant et al, 2014]. Olk, Dinu, Zielinski, and Kopper [2018] found that having a number of "distractor" objects or objects with similar colors can disrupt attention in VR just as in 2D situations.

3 Cellverse

To address students' ideas about cells, we have developed Cellverse, a VR based game to help students learn cellular biology. Two students play together, one using an Oculus Rift with Touch controllers, the other on a tablet or laptop. Upon starting the game, players are given a challenge: the cell has one of five possible classes of cystic fibrosis (CF). Use the information given to diagnose the cell. The players begin by exploring the three-dimensional cellular environment. The players' roles have complementary abilities and information, so they need to communicate and work together to succeed. As CF is a genetic disease, players' investigations have a genetic component, leading them to interrogate cell processes, especially protein synthesis. To introduce players to the collaborative part of the game, we developed a set of single player activities called "inquiries". These "inquiries" are designed to introduce players to the hand controllers, the cell environment and to critical concepts in the larger game: protein folding, translation, membranes, and ions. This study focuses on the single player introduction to the game that introduces students to the process of translation of RNA into proteins.

3.1 Game play

In *Cellverse,* the player is challenged to find clues to diagnose the cell. Once players put on the headset, they are introduced to the controllers by FR3ND, a non-player character who accompanies and advises the player throughout the game. During the tutorial, players learn how to move through the cell and how to use a clipboard for information and to take samples. Once players have mastered the controls, players are prompted to open the dashboard. The dashboard describes their mission, or inquiry, to travel to the organelle with translating ribosomes. The dashboard and cell environment are shown in Figure 1.

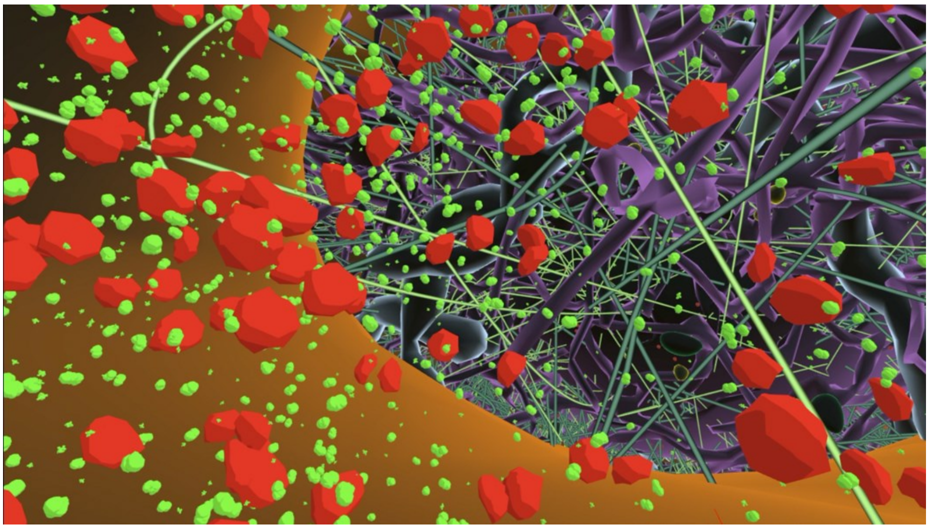
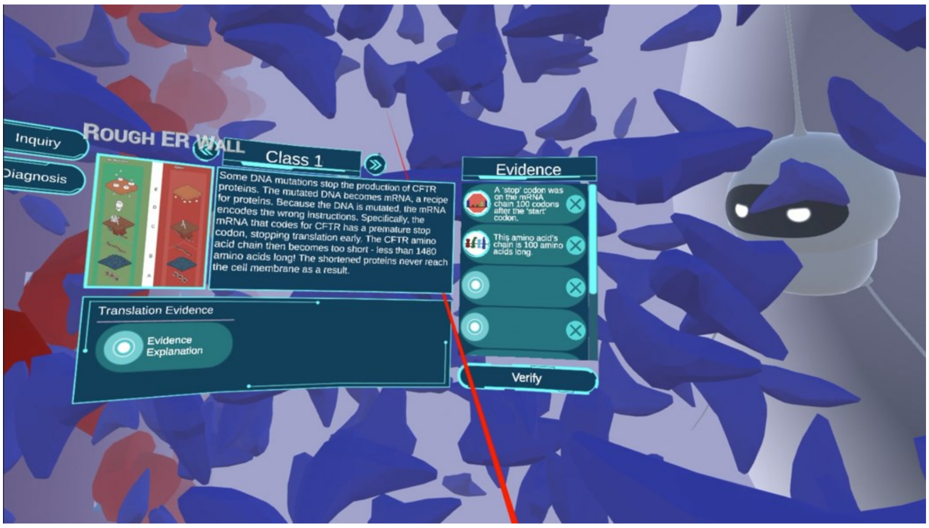


Figure 1: A screenshot of the game, showing a densely packed cellular environment

The cell environment is densely packed, showing students the complexity of actual cells compared to traditional textbook depictions. Players are able to learn about different organelles by selecting them and toggling the clipboard to see descriptions of organelle function, enabling them to either learn about organelles, or reinforce their understanding in a rich and complicated context. Once they reach the endoplasmic reticulum (ER), FR3ND prompts the player to use a "nanobot" to see the ER in more detail. Showing players what would be visible at a micro scale (organelles) and a nano scale (RNA and amino acids) reinforces the relative scale of organelles to nucleotides. In nanoscale view, the player is able to view messenger RNA moving into a ribosome and being translated into an amino acid chain. The player can also move through a translocation channel on the ER to view the amino acid chain on the opposite side. Once the player is ready, they open the dashboard and verify their evidence, then review different types of CF to connect the evidence they gathered during the game to the diagnosis of type of CF. The blue green dashboard and FR3ND are shown in the nanoscale environment in Figure 2. The range of time players needed to play this part of the game is 20-40 minutes.



Some DNA mutations stop the production of CFTR proteins. The mutated DNA becomes mRNA, a recipe for proteins. Because the DNA is mutated, the mRNA encodes the wrong instructions. Specifically, the mRNA that codes for CFTR has a premature stop codon, stopping translation early. The CFTR amino acid chain then becomes too short - less than 1480 amino acids long! The shortened proteins never reach the cell membrane as a result.

A 'stop' codon was on the mRNA chain 100 codons after the 'start' codon.

This amino acid's chain is 100 amino acids long.

Figure 2: A screenshot of nano view, showing the dashboard on the left and FR3ND on the right

4 Method

4.1 Research questions

With these factors in mind, we proposed the following research questions:

RQ1. How does playing an immersive virtual reality-based game influence players' conceptions of cells?
RQ2. How do learners respond to the virtual reality approach to learning? How does experience in VR impact student learning?

4.2 Participants

The sample consisted of 154 students whose age range is between 14-19 years (mean 16 years) from two urban diverse high schools located in the US. A total of 111 students completed pre and post surveys and post-game interviews. In school 1, 10 students were first year honors biology students and 76 students were senior level biology students. In school 2, all students (25) were part of an AP biology class. Participants' demographic information including gender, ethnicity, VR experience, and whether they described themselves as game players are included in Table 1 below.

Gender, count, percent		**VR Experience, count, percent**	
Female	59 (39%)	Yes-many times	22 (14%)
Male	84 (55%)	Yes-only once	62 (40%)
Other	2 (1%)	No	69 (45%)
Missing data	8 (5%)		
Game Player, count, percent		**Race/ Ethnicity, count, percent**	
Definitely yes	63 (41%)	Asian	3 (2%)
Probably yes	31 (20%)	Black-African American	7 (5%)
Might or might not	23 (15%)	Hispanic-Latino	93 (60%)
Probably not	23 (15%)	White	36 (23%)
Definitely not	13 (8%)	Prefer not to answer	7 (5%)

Table 1: Demographic Information of Participants' Gender, VR experience, Game experience, and Race/ Ethnicity

4.3 Study procedure

Students completed an online pre-assessment and were asked to draw a cell before starting the game. Students participated in the game individually during class time. Each student was introduced to the headset and controllers, given an overview of the purpose of the game, and played the game for a maximum of 25 minutes. The research staff answered questions about the technology (e.g. controllers, headset position) but not about the game. Once finished, students participated in a brief five question interview, which was recorded with the student's permission. They were asked to draw a cell again and describe in words how their ideas about cells may have changed as a result of the game. All students took an online post-assessment the week after completing the game.

The pre-assessment included questions about knowledge of cellular organelles, size of organelles, and quantity of organelles in the cell and cell processes, self-efficacy, interest in science, and perception of presence in the game environment. Multiple choice questions were scored, then coded as 0 (incorrect) or 1 (correct). Data were input into SPSS for analysis. Interviews were transcribed and coded by two coders. Inter-reliability and percent agreement between coders was found to be .90.

5 Results

5.1 Cell biology knowledge

A paired sample t-test was conducted to evaluate the impact of game play on students` cell biology scores. The content was divided into five parts: size and scale, number of organelles, organelle functions, translation, and membrane. There was a statistically significant decrease in size and scale scores from pretest (M=.50, SD=.12) to post test (M=.28, SD=.12), t (110) =15.27, p<.05 (two-tailed). The eta squared statistic (.68) indicated a large effect size. There was no significant difference between pre and post test scores for the other contents (number of organelles, organelle functions, translation, and membrane).

5.2 Level of class and cell biology knowledge

One-way between groups analysis of covariance was conducted to compare the influence of class level (first year students in School 1, Seniors School 1 and Seniors School 2) on students` post biology scores. Participants` pretest cell biology scores were used as the covariate in this analysis.

Preliminary checks were conducted to ensure that there was no violation of assumptions. After adjusting for pretest scores, there was a significant difference between class levels on post-test cell biology scores. F (2, 107) =17.63, p<.05, partial eta squared .25. Bonferroni procedure was applied to check post-hocs, seniors of School 2 (M=.46, SD=.09) had significantly higher mean scores on the post-test than first year students of School 1 (M=.27, SD=.09).

5.3 VR experience and post cell biology knowledge

One-way between groups analysis of covariance was conducted to compare the effectiveness of students' self-described VR experience (many times, only once, none) on students` post biology scores. Participants` pretest cell biology scores were used as the covariate in this analysis.

Preliminary checks were conducted to ensure that there was no violation of assumptions. After adjusting for pretest scores, there was a significant difference between different VR experiences on post-test cell biology scores. F (2, 107) =448, p<.05, partial eta squared .08. When the Bonferroni procedure was used to check post-hocs, students with more VR experience had higher cell biology scores after game play: students who had experienced VR many times (M=.37, SD=.10), only one VR experience (M=.32, SD=.11), and no VR experience (M=.30, SD=.11).

5.4 Cell drawing results

The total number of organelles included across all student drawings before the game is 430, and after the game the number increased to 536. The number of each type of organelle included in students' cell drawings before and after the Cellverse game are in Figure 3. Lysosomes (f=38) and ribosomes (f=28) are the organelles that had the greatest increase between pre and post cell drawings (see Figure 4). The other types of organelles that increased in post cell drawings are rough ER, smooth ER, vacuoles, RNA, mitochondria, and Golgi body. Lysosomes, ribosomes, rough ER, smooth ER, vacuoles, and RNA are the organelles that students encounter and interact with most during the game play.

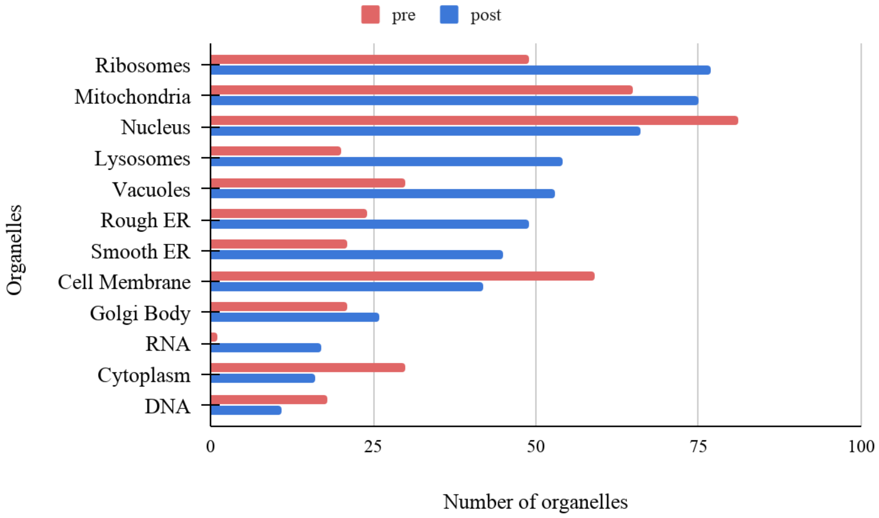


Figure 3: Number of organelles in cell drawings before and after the game

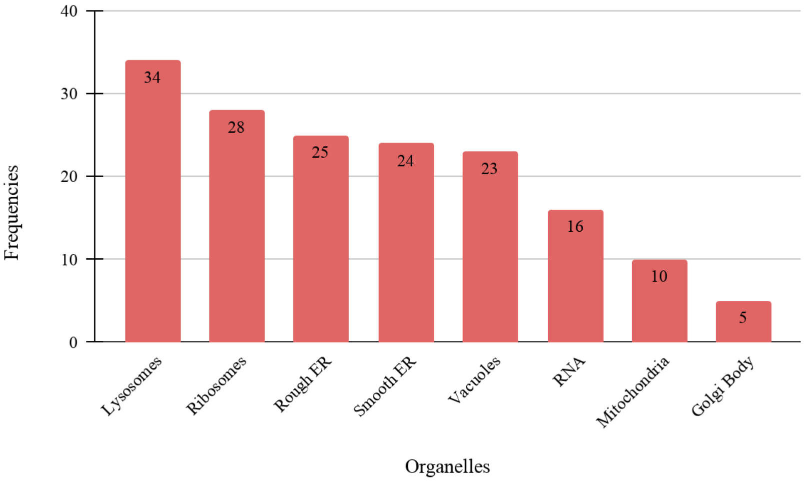


Figure 4: Increase in appearance of organelles in cell drawings

A summary of representative cell drawings before and after game play are included in Figure 5. Students added more organelles with labels and details after game play. Moreover, the sizes and shapes of organelles changed in post cell drawings. While pre cell drawings look like figures in textbooks (disc-like, have round-shaped borders, and include round shaped organelles), post cell drawings are more complex, have unstructured borders, and display more organelles with different shapes and sizes.

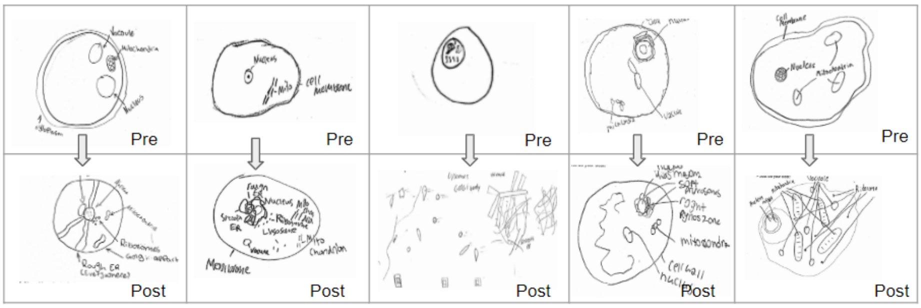


Figure 5: Cell drawings before and after game play

On the bottom half of the cell drawing sheet, students were asked to write about how their ideas about cells changed after game play. Responses of students were coded, and the following frequencies were found for each code (see Table 2).

Code	Frequency
Number of organelles	18
Size, Scale, and Shape	17
More Complex	15
Functions of organelles	11
Know what cells actually look like	10
Location of organelles	9

Table 2: Effect of playing game on students' knowledge of cell environment and number, size and scale, and function of organelles

The most common change among students was an awareness of different types of organelles and the total number of organelles present in the cell. The VR experience helped students conceptualize the density of the cell environment. One student explained that the VR environment helped them appreciate "The volume of the cell and reality that there are thousands of organelles rather than just a few." Students also described a change in their overall ideas about the cellular environment.

> "After playing the game, I was able to see how the organelles move around. It also helped me put into perspective how many organelles there are in a single cell. It

> also helped me see where the organelles are in relation to other organelles, for example smooth and rough ER are near [the] nucleus."

Many students linked the interactive VR format of the game to their new ideas of cells. One student explained "My ideas changed after playing the game because I was able to see up close how cells function work together and look like."

Students mentioned how the game format was helpful in portraying cells as a complex environment, especially compared to 2D images. One student explained, "The game reinforced my ideas of how complex human cell systems are. It is easier to understand cellular systems in a 3D setting compared to a 2D diagram on paper."

5.5 Mini-interview Results

95 students were interviewed after game play and were asked for their experiences and feelings about the game. Student responses were coded, and frequencies were found for each code (see Figure 7). Each code was categorized under three factors: technology, content and students (see Figure 6). In terms of technology factors, students described the game as being interactive (frequency of mention =47) and visual (f=39), as well as realistic and immersive (f=38). Students described the game as realistic, immersive, and interactive, and almost all of the students felt that they were present in the game environment (f=111). One student explained:

> "It was really cool to, uh, look around the cell and be in there cause you normally don't get that opportunity to visualize it and it was really cool that you could move around and see all the different organelles and get more information about it, um...yeah. It was a great experience."

Other students described how they liked being surrounded by the cell and being able to move around and explore in the environment. When asked what they learned, students stated that they learned about cell knowledge (names of organelles, their functions and translation) and organelles` relative sizes.

> "I feel like probably the biggest thing I was able to learn was the relative size of each, especially compared to one another. I feel like other than that I didn't. There wasn't a ton of new information that I learned but probably like the sizes in relation to one another and where they are in relation."

However, students also felt lost and confused due to navigation problems (f=29) and some experienced difficulty acclimating to the novel environment of VR (f=7). These aspects of technology might have an impact on students' experience.

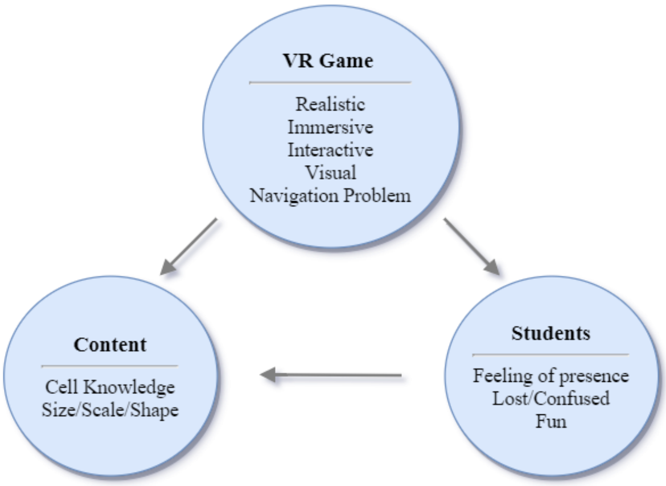


Figure 6: Codes of the mini-interviews

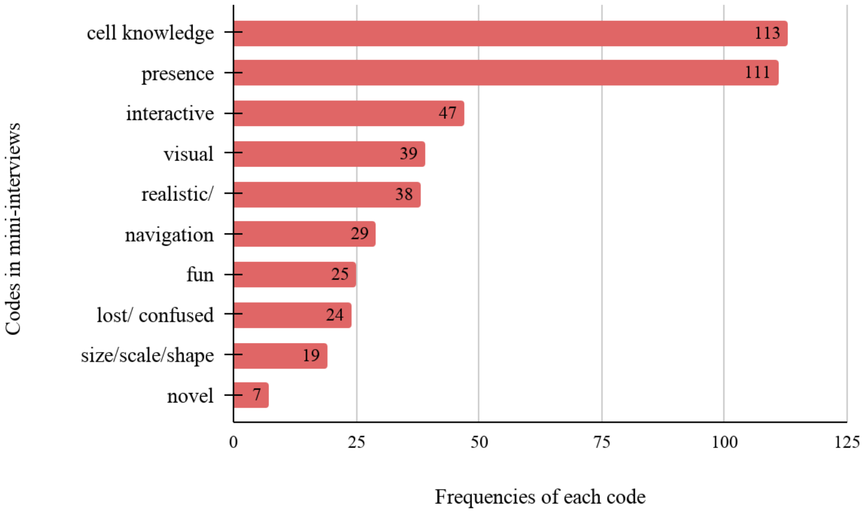


Figure 7: Frequencies of each code in game mini-interviews

6 Discussion

This study examined the impact of a VR based game on students' understanding of cells and the cell environment. Results showed that students in this sample initially had misconceptions about cells. Concurrent with prior research, [Çeliker 2013; Vlaardingerbroek, Taylor, & Bale, 2014] students' initial drawings did not represent the number, scale, and detail of organelles present in the cell. In their interviews, students recognized that prior two-dimensional materials did not capture the complexity of the cell, and that those representations may have initiated incorrect ideas [Vlaardingerbroek, Taylor, Bale, 2014]. Additionally, they explained that viewing the cell from the inside helped them gain an appreciation for the cell as a complex and dynamic environment. They also appreciated the interactive nature of the game, describing the game as more motivating and fun than traditional methods of learning about cells.

Similar to Dauer, Bergan-Roller & King, [2019], we used students' drawings to make their mental models visible. The change between pre and post cell drawings suggests that the game experience contributed to a change in students' mental models about cells. Students' post drawings were more detailed and contained more labeled organelles. Post drawings included more of the organelles that were present in the game, such as vacuoles, lysosomes, ribosomes, and representations of the Endoplasmic Reticulum. Ribosomes and the ER were central to the game; lysosomes and vacuoles were part of the introductory sequence of the game. The increase in those organelles may indicate that students focused on the organelles that were most useful to them in playing the game [Witmer & Singer, 1993, Wirth et al., 2007].

Despite learning about the cell environment and specific organelles in the cell, students did not improve in their factual knowledge of cells as measured by the posttest. This could be due to a few factors. Prior research indicates that VR may be better for having students learn procedural knowledge, while slide decks may be better for learning factual knowledge [Parong & Meyer, 2017]. The focus on the game goal may have focused students on particular aspects of the cell, and reduced the time students spent exploring the environment [Witmer & Singer, 1993, Wirth et al., 2007]. Research suggests that simulations encourage students to try many different configurations [Thompson et al., 2016], and may prompt students to investigate more aspects of the virtual environment. Starting the game with simulations to explore the concepts in the cell and then introducing the game goal may help students learn more about the overall cell. Future research will include additional scaffolding to encourage more time in cell exploration.

Students reported both a high level of presence and of feeling "lost", indicating that they may have been overwhelmed by the VR format. For many students, this was their first or second VR experience. While the novelty of the game may have been motivating, it is likely that students spent time and mental effort acclimating themselves to the virtual space. Students with more VR experience fared better on the assessments. It may be useful to have inexperienced students play a different VR game before starting Cellverse. Study results also suggest that students with higher levels of biology knowledge may gain more from the game, as students in school 2 fared better on the post-tests than students in school 1. Additional background knowledge may help students leverage embodied and embedded learning in the complicated VR environment.

Although students reported that their concept of relative size and scale of organelles in the cell improved, this was not reflected on the post test. Moving throughout the cell changed the relative size of the organelles; students' reports of feeling lost may complicate their ability to assess relative size and scale. Past studies show that students benefit from having a reference point for comparison [Jones, Taylor, Broadwell, 2009]. The non-player character FR3ND was the same size as a ribosome, however the comparison point was not explicitly pointed out to the students and few students made the connection on their own. The focus on the game goal may have prevented them from taking the time to observe specific organelles in relation to each other. In future iterations, the comparison point will be clarified, and tasks will be centered around that comparison point to create a more specific goal.

7 Conclusion

Developing understanding of biology is critical to be an informed citizen. Cells are an important concept in biology that students find challenging to understand. This study explored how an interactive, inquiry based, VR learning game can impact high school students' mental models of cells and cellular biology. Based on data from student drawings, pre and post-tests, and interviews, we conclude that students gained a better idea of the complexity of the cell environment, the number of organelles present, and expanded their knowledge of the types of organelles found in the cell. Students found the experience fun, engaging, and felt that the format helped them develop more authentic ideas about cells. Pretest/ post test results show that students did not improve in their factual knowledge about cells or about size and scale. Future research will incorporate more scaffolding during the experience to encourage students to spend more time exploring the environment and to have a point of reference for estimating size.

Study outcomes support further exploration into the use of VR as a learning tool for helping students understand complex biological environments. Students felt present in the dynamic world of the game and appreciated the ability to interact with material that normally is taught with static, two dimensional materials. As technologies such as VR become more widespread, designers and educators should incorporate scaffolding into these environments to help guide learning.

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