Iterative user and expert feedback in the design of an educational virtual reality biology game

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ABSTRACT
This study focuses on an educational game titled Cellverse, a two-player cross-platform VR project intended to teach high school biology students about cell structure and function. In Cellverse, players work in pairs to explore a human lung cell and diagnose and treat a dangerous genetic disorder. Cellverse is being designed by the Collaborative Learning Environments in Virtual Reality (CLEVR) team, an interdisciplinary team consisting of game designers, educational researchers, and graduate and undergraduate students. Using a design-based research approach, we have enlisted the help of both subject matter experts and user testers to iteratively design and improve Cellverse. The objective of this paper is to share how user and expert feedback can inform and enhance the development of learning games. We describe how we gather and synthesize information to review and revise our game from in-game observations, semi-structured interviews, and video data. We discuss the input of subject matter experts, present feedback from our user testers, and describe how input from both parties influenced the design of Cellverse. Our results suggest that including feedback from both experts and users has provided information that can clarify gameplay, instruction, subject portrayal, narrative, and in-game goals.

Introduction

As the technology becomes more affordable, virtual reality (VR) is becoming increasingly viable in K-12 and undergraduate circles (Castaneda, Cechony, & Swanson, 2016; Thompson, Kaser, & Grijvala, 2019). Many of the educational experiences currently available in VR address learning in science, technology, engineering, and mathematics (STEM) domains. Biology VR games, animations, and simulations have been developed for both educational and for entertainment purposes. Applications of VR in biology have been shown to improve high school students’ understandings in abstract concepts in microbiology (Minogue, Jones, Broadwell, & Oppewall, 2006; Tan & Waugh, 2014); to improve college students’ understanding of molecular structures (University of Stavanger website, 2017); to enhance learning of anatomy (Jang, Vitale, Jyung, & Black, 2017); and to enable virtual laboratories for students (Potkonjak et al., 2016; Roschelle, Martin, Ahn, & Schank, 2017). Science, technology, engineering, and mathematics (STEM) topics have been the focus of many educational games (Bonde et al., 2014). Games like InCell and Cellscape, which are accessible via commercial VR headsets, take users on virtual “tours” of cells and cell functions (Cellscape website, 2017; InCell Website, 2017). Although these games are immersive, most of them are neither interactive...
nor collaborative, and allow only for single-player experiences. Furthermore, many of them do not depict cells in an authentic manner, taking liberties with size and scale, density, and number of organelles without regard for how these depictions may affect learners’ conceptions.

School curricula are beginning to incorporate twenty-first century skills such as critical thinking and collaboration (Fiore et al., 2017); consequently, collaboration within VR has also become relevant to educators (Merchant et al., 2012). Cross-platform collaborative games can blend both immersive VR and 2D platforms (Gugenheimer, Stemasov, Sareen, & Rukzio, 2017). Games like Black Hat Cooperative and Keep Talking and Nobody Explodes provide different user and environmental interfaces to in- and out-of-VR players and challenge them to cooperatively solve puzzles or other fast-paced challenges. However, there are few viable examples of educational games that involve two or more players in- and out-of-VR.

The goal of the Collaborative Learning Environments in Virtual Reality (CLEVR) project is to develop educational games. Our first game, Cellverse, aims to help students learn about cell structure, the process of transcribing DNA to RNA, and the translation of RNA to proteins (the central dogma). We have used a design-based research methodology (Collins, Joseph, & Bielaczyc, 2004; DBRC, 2003), conducting tests and interviews with users and experts throughout the design process. While other studies have connected game design to research outcomes (Cheng, Rosenheck, Lin, & Klopfer, 2017; Clarke-Midura, Rosenheck, Haas, & Klopfer, 2013; Gauthier & Jenkinson, 2017, 2018), few studies document the cyclical process of collecting, reviewing, and integrating user and expert feedback into a game. This study focuses on the iterative design process so that game designers and researchers have an understanding of our pathway through designing Cellverse. Additionally, we document how we have infused subject matter experts into the design and feedback process. The data we collected have helped us iteratively create an experience that offers learners rich, immersive opportunities to collaboratively investigate and explore the cell from the inside out.

**Theoretical background: STEM learning theories and collaborative games**

Well-designed game-based learning experiences have the potential to engage students in the learning environment through different educational pathways. For example, in one segment within the simulation The Body VR: Journey inside a cell, viewers enter the bloodstream and experience the journey of a red blood cell spreading oxygen into the body. Being in the environment enables experiential learning, where viewers can learn through placing themselves within a virtual space (Kolb, 1984). Research suggests another potential added value for enabling learners to interact directly with the environment, enabling embodied cognition. The embodiment theory of learning proposes that knowledge is best imparted when learning events relate to physical actions (Kiefer & Trumpp, 2012). Weisberg and Newcombe (2017) further develop this theory by linking embodied cognition to the development of spatial awareness, which is identified as an important part of understanding in STEM domains (Stieff & Uttal, 2015). Thus, incorporating physical movement and gesture can increase an individual’s capacity to learn complex domains by creating multiple ways of interacting with material (Stieff & Uttal, 2015). For example, students who learned about biomolecular models with haptics were better able to understand how molecules fit together than students using models without haptics (Schönborn, Bivall, & Tibell, 2011). Studies of embodied learning environments also suggest that direct manipulation of physical or virtual representations of materials can enhance learning as compared to traditional methods (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004; Webster, 2016). The design of the CLEVR project Cellverse incorporates embodied learning by requiring students to use gestures and movement to navigate through the cell. Research connecting embodied cognition and virtual reality is still nascent (Weisberg & Newcombe, 2017); however, the research base on embodied cognition began long before virtual reality’s rising popularity and includes research on manipulatives in mathematics (Martin & Schwartz, 2005; Schwartz & Martin, 2006), and in 2D video games such as Tetris (Kirsh & Maglio, 1994; Pouw, Van Gog, & Paas, 2014).
The game-based format of Cellverse provides a high degree of interaction between students and the concepts included in VR environment (Jang et al., 2017; Lindgren, Tscholl, Wang, & Johnson, 2016). A significant piece of this interaction is movement around the cellular environment, which introduces a spatial dimension to a cell that is often missed in 2D textbook representations. The two players involved develop spatial understanding of the virtual environment over time to locate clues and figure out what is wrong with the cell. The game provides ongoing textual and visual feedback to the players, which may also assist the learning process (Merchant et al., 2012). In creating Cellverse, we intend to present a topic that is often passive and vocabulary-based into an experience that builds on our current understanding of embodied learning by incorporating action to cognition and development of spatial understanding of cells. Conducting ongoing user testing enables us to gauge the educational effectiveness of the game and the physical comfort of users in the virtual environment. Furthermore, user testing allows us to document development of embodied cognition and spatial understanding through gameplay while adjusting the design based on feedback from experts in the field. This paper documents how we conduct, connect, and act upon the information we gather from novice and expert users and how that information has helped us gauge the effectiveness of our design.

### Collaboration in embodied learning

Education has expanded beyond conceptual and content knowledge to build students’ twenty-first century skills, such as critical thinking and collaboration, which will help students prepare for the workforce (OECD, 2017). One area of interest is in collaborative problem solving. Collaborative problem-solving links individuals in “sharing the understanding and effort required to come to a solution and pooling their knowledge, skills and efforts to reach that solution” (Fiore et al., 2017). As research in blended reality collaborative environments continues to develop (Bower, Lee, & Dalgarno, 2017), broader research on collaboration becomes more applicable and useful.

Many current educational games are single player, leaving an opportunity to develop multi-player games (Coleman & Money, 2019). Supporting collaborative problem solving requires individuals to actively communicate, interact, negotiate, and establish social relationships among the group. Johnson and Johnson’s (2005) theory of positive interdependence suggests that optimal collaboration originates from a situation where all individuals need to contribute for the group to succeed in its mission. Laal (2013) further divides interdependence into nine subcategories; for this study, we focus on their category of “role and resource interdependence”. In order to be effective, collaboration has to be integrated in the game design. For example, game designers can use roles and resources to foster collaboration (Thompson et al., 2018). Roles are an important construct in helping team members negotiate interactions in virtual environments (VE) and VR (Koutsabasis, Vosnakis, Malisova, & Paparounas, 2012), and in determining who should complete tasks (Li & Zhou, 2016; Lui & Slotta, 2014). Resource interdependence can be fostered by giving individuals access to different technology such as a head mounted display (HMD) and a tablet (Gugenheimer et al., 2017), or giving each participant varied different tools and capabilities (Jensen, 2017). One goal in this design-based research approach is both imagining and testing how our game can establish role and resource interdependence among learners.

Another construct that is useful in exploring the opportunities for collaborative problem-solving is the concept of productive failure. Productive failure, studied by Kapur (2015), suggests that deeper learning can occur in situations when participants’ learning generate solutions to an unfamiliar concept with limited or no support. In Kapur’s experiments, students were given educational activities to complete without educator “cognitive guidance or support”. Allowing students to leverage their previous knowledge and natural intuition required them to experiment with solutions and potentially fail before succeeding, enabling greater learning and retention than fully guided experiences. Some modern video games are a particularly insightful source of the power of productive failure – levels may require multiple attempts and strategies to complete (Anderson, Dalsen,
Kumar, Berland, & Steinkuehler, 2018; Gauthier & Jenkinson, 2018). Failure is integral to gameplay; a well-designed game enables players to embrace process as part of learning to succeed (Gee, 2014). In designing Cellverse, we consider the role of productive failure as a careful balance between challenge and support.

**Designing Cellverse**

Within the framework of design-based research, we iteratively investigate and improve our game throughout the duration of its development (Collins et al., 2004; DRBC, 2003). Kurilovas (2016) recommends using both a bottom-up (user-based) and a top-down (expert-based) review to evaluate the quality of VR experiences. User-based testing recognizes the importance of understanding how the users interact with the virtual environment, while experts provide insight into the technical quality of the system (Kurilovas, Serikoviene, & Vuorikari, 2014). While Kurilovas (2016) focused on experts in VR, we explore how experts in science and science education have informed game design. We propose three design conjectures (Sandoval, 2014) that link our theoretical and conceptual starting points to our inquiry into the process of creating the game.

1. Incorporating domain experts (top-down) in the vision and creation of a serious game will enable the design of an authentic representation of the cell.
2. Iterative user testing (bottom-up) will reveal the learning affordances (e.g. embodied learning) in the context of a biological cell.
3. Ongoing user testing will inform the creation of a cross-platform collaborative game.

The CLEVR project is funded by Oculus Education and was built to support the Oculus Rift system. Our team consists of education researchers, game designers, and undergraduate and graduate students skilled in programming, front-end development, UI design, 3D modeling, and/or digital art. Cellverse, the game, was built in Unity and programmed in C#, with cellular and protein models created in Blender and Maya or downloaded and modified from open-source sites like the Protein Data Bank.

**Methods and analysis**

**Subject matter expert interviews**

In the context of designing Cellverse, subject matter experts (SMEs) are individuals with knowledge of science and science education in cellular and molecular biology. We identified SMEs through online research, networking, and suggestions by the researchers through their professional networks. Upon meeting, we demonstrated the game and gathered their feedback. We prepared broad questions about their field of expertise and specific questions about the game with possible applications within Cellverse. During the interviews, members from our research, design, and implementation teams took notes and shared the notes with the experts after the meeting to confirm accuracy (Thomas, 2017).

**User testing process**

For formal playtests, we created a “Multiplayer User Testing Feedback Form,” which records user reactions and interactions with major facets of the game: tutorial, environment, gameplay mechanics, and multiplayer function. The user tested one of two interdependent collaborative roles – the explorer role, where they navigated the cell within the virtual reality environment, or the navigator role, where they accessed cell and disease information using a 2D touchscreen interface connected to the same environment. Depending on the role the user was assigned, they participated in a slightly different pre-testing procedure. In each test, a team member explained the
premise of the game, assisted users with the headset if applicable, and asked them a series of questions before, during, and after the game using a structured protocol. These questions were used to document and evaluate user interaction with Cellverse and to gauge our own ability to guide users through the experience. They were also designed to be open-ended, to allow users to be as honest and critical as possible. Some questions have been altered, revised, or removed depending on our needs. Demographic descriptions and the number of user testers by level of schooling is provided in Table 1.

The feedback notes contain observations on user behavior and information about users’ backgrounds (such as student, teacher, researcher). User tests were recorded on video and stored in a private server where team members reviewed and took notes on significant findings. After the playtests, members of the research and design team independently reviewed the interview responses and observation notes. Team members noted themes that emerged from each session inductively. The team convened, reviewed and discussed the findings, and documented the findings for the next design iteration.

All user names have been replaced with pseudonyms in this analysis; while the team knows the first names of participants, they are otherwise anonymous. The study has been reviewed by the university’s Institutional Review Board (1709095354). Both users and subject matter experts gave consent to include their responses in the study.

Results

The results below are presented chronologically, from spring 2017 to early summer 2018. We will first discuss the input of SMEs (top-down), then present feedback from our user testers (bottom-up), and finally explain how input from both parties influenced the design of Cellverse at that respective stage. We will also discuss the decisions that we made regarding SME and user suggestions, which include changes we added to the game and suggestions that we ultimately chose not to implement. We will finally discuss features of the most current version of Cellverse (as of summer 2018).

Summer 2017 – developing the Cellverse environment

Subject matter experts (SME) feedback

Between May and July 2017 we interviewed SMEs to further inform the overall design and direction of the game. The primary topics of discussion included depictions of size and scale in VR; educational games within a classroom setting; and misconceptions about cells, viruses, and the “life cycle” of viruses.

We consulted experts experienced in various fields of microbiology, particularly virology, as we initially explored viruses as a context for the games. After learning about the diversity in how viruses infect and multiply in cells, we decided to focus on genetic diseases, which would focus on the important topic of protein synthesis. Many of the virus-based suggestions regarding Cellverse gameplay thus became obsolete and were not implemented. We also started using the Next Generation Science Standards (NGSS, 2013) as a baseline for the educational content of Cellverse.

| Table 1. User tester demographics, summer 2017–June 2018 |
|---------------------------------|----------------|
| User tester type                | Number of testers |
| Undergraduate students          | 3               |
| Graduate students               | 10              |
| Middle/High school students     | 2               |
| Middle/High school educators    | 17              |
| Researchers, scientists, other professionals | 6 |
| Other                           | 11              |
| **Total**                       | **49**          |
**Feedback integration into design**

The first iterations of *Cellverse* investigated various forms of movement and scaling and were created in simplistic VR environments that paid little heed to true scientific accuracy. The navigation method that we chose to continue working on, coined the “Spider-Man” style (Figure 1), allows users to move their virtual forms around the cell environment using a pointer attached to the right-hand touch controller. “Spider-Man” allows for a significant amount of free movement and has been the movement style that we have used for subsequent iterations.

**Fall 2017**

**SME feedback**

Interviews during the fall focused on single-player interaction and exploration within the VR space. Most of the SMEs invited to test and discuss the game were experienced with cell biology, specifically cell structure and function, and they provided helpful input on the accuracy of our visual depictions and in-game science.

Input from SMEs was influential in constructing *Cellverse* as a scientifically accurate and visually interesting human epithelial lung cell. We implemented suggestions from David Goodsell, a molecular biology professor and artist including creating a more polarized cell (as would happen in most lung cells), building a larger and more accurate nucleus model among other major organelles, and creating visual “markers” for genetic disease, and increasing the overall density of *Cellverse* to make it more realistic. Professor Iain Cheeseman and his graduate students suggested several ideas for cellular animations, which add a “living” quality to *Cellverse*.

We interviewed Dr. Hongmei Mou, a specialist in personalized medicine for lung and airway diseases. Dr. Mou’s input solidified our decision to focus on the genetic lung disease cystic fibrosis (CF). We also learned about the numerous classes of CF, and used them to compose a list of symptoms that players must consider during the game.

We did not incorporate all of the SME’s suggestions. For example, technological limitations prevent us from fully recreating the density or viscosity of the cell to the level that Dr. Goodsell suggested. Nausea among players was another factor – full visual representation of the cell’s contents could potentially overstimulate certain persons, and low frame rate due to excess due to excess in-game elements is known to cause motion sickness in VR users (Spzak, Michalski, Saredakis, Chen, & Loetscher, in press). Managing user comfort prompted us to be selective about what we decided to

![Figure 1. “Spider-Man” style navigation from early summer prototype.](image)
animate in the game. The cell is a dynamic place, and not all of the cellular environment can be captured simultaneously with our current technology. Thus, we focused on the key elements of motion related to the RNA-to-protein interface at the endoplasmic reticulum.

**User testing feedback**

User testing, which began in earnest during the fall of 2017, focused on comfort, in-game movement, environmental feedback, and users’ understandings and expectations regarding cell structure. At this point we had not yet added goals or collaboration to the Cellverse interface; the game was an explorable environment with minimal interaction.

**Reflections**

User testing suggested that the design should include an engaging environment that prompted individuals to link their biology understandings with the virtual experience. Nine of the 25 testers specifically remarked on the dense nature of the environment, focusing on prolific organelles like mitochondria and ribosomes. Six users also tried to connect their observations with their preexisting biology knowledge, calling out specific organelles such as mitochondria, ribosomes, and “lysosomes – I forgot about those.” Finally, three users described how the environment was fun. They gave affective feedback such as “It’s kind of amazing – it’s just fun. I don’t think my high school biology did cells justice.”

Users’ suggestions for the game fell under three major themes: direction, interaction, and aesthetic. Users requested more gameplay elements that would provide direction such as a “find-it list,” a “minimap,” or “given objectives” such as tutorials or quests. Many of these features are part of our ongoing design process and will be added over time. Users wanted more interaction with organelles in the cell and functionality such as “interactive elements on the left hand,” and toggleable “layers to the visuals.” For aesthetics, players wondered about the “choices made behind the color palette.” Five players wanted greater dynamism and to be able to see animated cell processes.

**Improvements**

Authenticity is one of our major goals and is something that is not always integrated into biology visualizations. Our SMEs recommended realistically dense environments that could support deeper thinking about cell processes and anomalies, and our users were surprised and engaged by those environments. Several players mentioned that they wanted to see a “task list,” a “map,” or simply more information, which were not in the game build at that time but were slated for future development. User requests were later reflected in some of our next steps, which included developing a game goal, increasing the methods of interacting with the environment, and making Cellverse more visually engaging.

**Feedback integration into design**

We remodeled our generic-looking cell as an epithelial lung cell in anticipation of possible diseases that could be used in-game. We increased the model count of several major organelles, including mitochondria and lysosomes; we also added a network of microtubules to better illustrate the cell’s shape (Figure 2). By the end of the fall semester, we had rebuilt Cellverse into a larger, denser, and more visually interesting environment.

**Winter 2018**

We focused primarily on implementing suggestions and concentrating on user testing from January 2018, maintaining contact with a smaller set of SMEs to confirm that our game remained scientifically accurate.
January 2018

A total of ten users tested the Winter 2018 version of Cellverse and completed the feedback form. Collaboration was first introduced in the January playtest, where the explorer (in-VR) had an internal view of the cell and the tablet user, or navigator, had a birds-eye view of the cell and a “tasklist” of disease symptoms they were expected to search for within Cellverse (Figures 3 and 4). The task list was influenced by discussion with genetics and disease experts from the fall and contained a list of possible genetic disorders that could be diagnosed by the absence, presence, and/or malformation of certain cell structures. The navigator also had access to a “beacon mode” that allowed them to

Figure 2. Fall 2017 Redesign of Cellverse and its organelle models. Shown are spawned mitochondria models that illustrate the density of the cell’s contents.

Figure 3. Screenshot of VR view prototype, circa winter 2018, illustrating color palette shift and increased density of Cellverse.
place beams of light within Cellverse for the explorer to see. (This function was replaced by a different function, which we will describe below in “Current version of Cellverse”). The explorer and navigator roles were designed to require users to work together to solve the problem.

Our user feedback, particularly from navigators, suggested that having a partner was useful (2 of the 10 January 2018 group of users), but ultimately unnecessary (3 of the 10 users). Although explorers observed that “it was nice to have a second opinion,” navigators commented that “I could have done it all by myself” because “I had the description of the disease and my partner didn’t.” Users gave suggestions on how to better involve partners, including understanding the different views of Cellverse and accessing interactive tools that can affect each partner’s view.

**Improvements**

This playtest enabled us to focus on balancing the information between players during the game, and we drew upon the users’ suggestions to do so. We made sure that players know that there are two views and have a sense of what their partner might see. We made the navigator’s view even more distinct from the explorer’s view by reducing the detail in the navigator view, requiring more interaction between the navigator and explorer. We adjusted the task list so that explorer observations were needed to progress in the game. To make the roles more distinct and interdependent, we began considering implementing a way to share information between the explorer and the navigator. To do so, we used scientific research techniques suggested by the SMEs such as “staining and tagging” as a way of maintaining authenticity in the game.

**Spring 2018**

**User testing feedback**

As the length and complexity of the game increased we conducted more focused and longer user testing sessions with fewer participants. For March 2018, we tested the game with four people, or two explorer/navigator pairs. In the March playtest, we realized that we needed to continue to balance information by clarifying labels in the tutorials. Additionally, the navigator was still leading the collaboration, which suggested there needed to be more balance of power between the partners.

Feedback from the May 2018 playtest suggested that we made progress on our goal of collaboration, as all four playtesters worked together during the activity as opposed to one partner taking
over. One player explained she and her partner worked together because “I had examples and definitions, [and] I had to ask what he was seeing and comparing”, while another mentioned that they had to ask the partner who was inside the cell for “specific names and colors” to progress in the game. Having a partner also helped users identify and understand the objective of the game.

Players still requested the ability to change viewpoints to get different perspectives on the cell, and to be able to go inside the nucleus. These requests foreshadowed our work on another upcoming aspect of the game, a “nanoscope” view, to allow the explorer to view organelles and cell functions at a smaller scale and thus with much greater detail.

**Summer 2018**

Summer 2018 includes our most recent version of Cellverse at the time of the writing of this article. We spoke to several medical researchers to further improve our understanding of the effect of cystic fibrosis within lung cells. We have also maintained contact with preexisting SMEs and have continued to develop CLEVR and Cellverse in a scientifically accurate manner.

**User testing feedback**

We had been testing paper prototypes of both explorer and navigator tutorials since January 2018 and received some constructive feedback on both. June’s playtest focused on the digital version of the game tutorial. In addition to digitizing the tutorials, the navigator view had been streamlined and improved. Four users tested the game during this period.

As surmised from user feedback, there are a few technical issues that we are addressing to further streamline the tutorial. Researchers observed that technical glitches within Cellverse resulted in confusion among users, including lack of guidance for some in-game functions and easily skippable tutorial instructions.

Some of our attempts to enable communication caused frustration between the players. For example, the tablet Cellverse view (depicting a “healthy” cell) was slightly different from the in-VR Cellverse view in terms of color and structure, which players did not always notice or communicate to each other. This resulted in confusion when players were attempting to describe certain organelles to each other in terms of color. For example, the centrosome, which was green in navigator view but is blue (a symptom of a fake placeholder disease) in VR view. Color confusion will likely be mitigated by the implementation of a microscopy technique described below, which means that the organelles in the Cellverse environment will initially start out in greyscale.

**Version of Cellverse as of summer 2018**

As of summer of 2018, Cellverse design and gameplay allows two players to collaborate and communicate while traveling around the virtual “world” of Cellverse, a human epithelial lung cell. One player wears a VR head-mounted display (the “explorer”), and the second player uses an interactive tablet interface connected to the same virtual space (the “navigator”). Each player is granted a different perspective of the cell; the navigator is given a “bird’s-eye” view of the same cell that can be rotated horizontally, vertically, and along the z-axis (Figures 5 and 6) while the the explorer has a three-dimensional internal view, where they are placed “inside” the cell and can travel around freely (Figure 7). The explorer can view descriptions of various cell organelles and components by selecting them and viewing a description on an adjoining clipboard. The navigator has a less detailed view of the cell and is provided with a reference of cell and disease information that the explorer cannot access. The navigator can communicate with the explorer, either verbally or by using simultaneous label-free autofluorescence-multiharmonic (SLAM) microscopy as a selection technique (You et al., 2018). SLAM uses light-based imaging to colorize living tissue as opposed to traditionally used dyes.
As previously stated, the virtual cellular environment is designed to reflect a realistic population of organelles—far more mitochondria and lysosomes than are regularly included in 2D representations. To prevent players from being mentally overwhelmed or nauseated by the sheer number of interactive items, explorers can physically select one organelle, move towards it, and turn on a virtual clipboard to review its function. The ability to select and move towards one organelle at a time scaffolds the experience so that players can focus on problem-solving even as they are navigating through the densely packed cell.

**Figure 5.** Screenshot of tablet view prototype as of July 2018, depicting the updated UI and more accurate shape of Cellverse. Disease information menu is open.

**Figure 6.** Tablet view prototype with SLAMming menu open.
We focused on balancing player roles, roles, and resources to foster collaboration (Thompson et al., 2018). The explorer’s view is more detailed and includes cell structures and gameplay functions not shown on the navigator’s user interface and lets them investigate nanoscopic cellular functions through the “nanobot” function. This affords the explorer the ability to view parts of the cell at an even smaller scale and see DNA, RNA, actin, proteins, ribosomes, and other structures too small to see at the “main” Cellverse view. The navigator has textual information pertaining to cellular disorders and diseases that are unavailable to the explorer, and access to a “SLAMming” mode that can select different organelles to make them visible to the explorer.

Some functions have not yet been implemented into playable builds of Cellverse but are currently under construction. After diagnosing the disease, players will rearrange DNA sequences to build a cure, much like how real-world scientists use gene therapy as a medical treatment for cystic fibrosis. We have also created a narrative that gives players context for the goal of the game, placing them as interns inside a hospital trying to help diagnose a sick patient.

**Discussion**

The top-down and bottom-up approach recommended by Kurilovas (2016) has been very useful in our design process. Consulting domain experts (top-down) during the process helped us design an authentic cell environment and focus the narrative on diagnosing and curing the cell. Experts have informed how we represent cystic fibrosis at the cellular level, have critically evaluated the accuracy of the portrayal of cell structures and processes, and have provided ideas about how players can interact with the cell environment. Our cellular depictions have changed directions based on information that experts have shared, which is information at the forefront of scientific understanding of the causes of cystic fibrosis. In seeking expert feedback, we are continually reminded of the dynamic nature of science knowledge.

User feedback helped us choose locomotion and selection techniques for the explorer, and the “pinch and zoom” and rotation functions the navigator has on the tablet. Interacting with a shared environment through a tablet and headset enabled us to establish possible roles and tasks. We learned that dividing resources such as information, tools, and viewpoints of the cell between the two players was critical in involving both players in the problem-solving process and developing a positive interdependence that involved both players in the problem-solving process (Thompson et al., 2018; Johnson & Johnson, 2005; Laal, 2013). While roles and resources may be viewed as distinct
aspects of interdependence, the two are tightly linked. Playing the game activated participants’ prior knowledge of cells; elaborating upon those ideas with a partner enabled participants to experience failure in a productive way (Kapur, 2015; Gauthier & Jenkinson, 2017). Productive failure also played an important role in encouraging players to explore, discuss, hypothesize, and test potential solutions to the game. User feedback regarding game difficulty allowed us to shape a gameplay experience that provided a challenge without making the solution too easy or infuriating to solve.

Our next set of SMEs are science educators and high school students. We will be shifting focus from teacher feedback on the game to teacher and student input regarding using Cellverse in the classroom with the goal of involving our target audience of high school students. Our research will explore these design decisions through the lens of learning goals and motivation for the topic of cellular biology. Moving forward, the concept of productive failure will become more salient, scaffolds designed to prompt collaboration will be tested in actual classroom settings, and we will gauge the effectiveness of the game in helping students better understand cells. One of our ongoing research questions regards the amount of support we need to give in order to ensure a fruitful learning experience.

**Conclusion**

As a cross-platform multiplayer VR and tablet game designed for the high school biology classroom, CLEVR is an ambitious project. We have taken into consideration that a game played in a collaborative classroom environment requires different design decisions than a single-player or multiplayer game in a purely virtual environment. The optimal way to discover and test our design decisions has been through iterative user testing, and we have developed CLEVR and Cellverse with that understanding in mind. This method will become more relevant as VR moves from a novel, limited experience to a more accessible and widespread educational tool. It is important to ensure that these games are both engaging and accurate.

Designing in virtual reality is resource-intensive and ensuring that these resources are well-allocated is an important challenge. Our aim in sharing this narrative is to help other creators consider top-down and bottom-up approaches in their designs by describing the data collection process and the resulting benefits. We hope this will provide inspiration for future researchers seeking to design and create educational games. As educational games are infused into curricula and formal education, it will become increasingly important to create games that both portray the subject matter in an authentic way and are also easy to understand and play in a classroom or other large group setting. Including multiple stakeholders as informants is time intensive; however, we believe this will result in a more effective and engaging experience.

**Notes**

1. Interview with Matthew Schnepps; Interview with Lourdes Aleman; Interview with Shane Tutweiler; Interview with David Walt.
2. Interview with Gail Jones; Interview with Connie Cepko; Interview with Daniel Kurtizkes; Interview with Tyler Krause.
3. Interview with David Goodsell.
4. Interview with Ian Cheeseman et al.
5. Interview with Hongmei Mou.
6. Interview with Brian Lin and Jaimee Elizabeth Hoefert, 26 July 2018.
7. To see gameplay videos of CLEVR, please visit education.mit.edu/project/clevr/.

**Acknowledgements**

CLEVR is supported in part by Oculus Education. We also acknowledge the MIT students, staff, scientists, and individuals who gave us feedback on the game.
Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Oculus Education [Grant Number Gift].

Notes on contributors

Annie Wang is a graduate student in the Comparative Media Studies Department at the Massachusetts Institute of Technology, working in the Education Arcade. Her interests lie in intercultural exchange, game design, and the power of new media technologies in disrupting and reshaping social science and STEM education inside and outside of the classroom. She graduated from Wellesley College with a degree in both Media Arts and Sciences (2D Design plus Computer Science) and History. Before joining the CMS program, she was cross-registered and later worked at the MIT Education Arcade and the Game Lab, where she worked to help design both touchscreen and virtual reality-based games for student learning. Outside of academia, she can usually be found researching and testing new recipes, getting lost in history museums, collecting pictures of dogs and seals, or debating the intricacies of video game lore.

Meredith Thompson draws upon her background in science education and outreach as a research scientist and lecturer for the Scheller Teacher Education Program. Her research interests are in collaborative learning, STEM educational games, and using virtual and simulated environments for learning STEM topics. She has a bachelor’s degree in chemistry from Cornell, a master’s in science and engineering education from Tufts, and a doctorate in science education from Boston University. She has two current projects: the Collaborative Learning Environments for Virtual Reality (CLEVR) is creating a cross platform collaborative game about cellular biology, and INSPIRE is a group of education professors who are using games and simulations in teacher preparation. Thompson uses those games and simulations when she teaches the STEP course: “Understanding and Evaluating Education.” She coauthored Envisioning Virtual Reality: A toolkit for educators, published by CMU’s ETC press. In her spare time, Meredith writes and sings music with her twin sister Chris (www.cmthompson.com), spends time with her two boys, writes poetry, and enjoys hiking in the woods.

Dan Roy is a research scientist at the Education Arcade and the Teaching Systems Lab, designing playful learning experiences for teachers and students alike. He is the lead game designer on the CLEVR project, inviting high school biology students to explore a cell in VR and collaboratively diagnose and treat a genetic disorder. He directs the ELK project, helping teacher candidates practice understanding what students know through roleplay conversations. Dan is also the founder of Skylight Games, a social enterprise inspiring a love of learning through play, starting with languages (Lyriko). Before his current roles, he worked with the Learning Games Network on games to teach language (Xenos) and science (Food Fight, Guts and Bolts), and with the Education Arcade, helping middle-schoolers build curiosity, intuition, and comfort in math through puzzles (Lure of The Labyrinth). He has an SM in Comparative media studies from MIT and a BS in computer science from Umass Amherst.

Katharine Pan is an MIT student pursuing a major in mechanical engineering and a minor in business. She is on MIT’s varsity swim team, and is a mentor to high school students through the Amphibious Achievement team. Her hobbies include sailing and exploring different cultures and cuisines.

Judy Perry oversees design, development, and research for several projects involving educational games and simulations, as well as their integration into formal or informal learning settings. Her work includes overseeing the TaleBlazer software platform, an online toolkit and mobile app for making and playing location-based augmented reality (AR) games. Perry is also project manager for CLEVR (Collaborative Learning Environments in Virtual Reality), which explores design and development of new approaches to educational applications of VR. Her research interests include playful learning, constructionism, design-based research (DBR), location-based games, participatory simulations (pSims), ubiquitous “casual” games, virtual reality (VR), augmented reality (AR), mobile games, and more generally, digital materials that foster engagement with STEM. Perry leads professional development training workshops for educators who want to implement STEP lab projects. She enjoys collaborating with other institutions (including zoos, nature centers, libraries, museums and science centers, living history museums, and K-12 classrooms) to develop experimental learning offerings.

Philip Tan is the creative director for the MIT Game Lab. He teaches CMS.608 Game Design and CMS.611J/6.073J Creating Video Games. For six years, he was the executive director for the US operations of the Singapore-MIT GAMBIT Game Lab, a game research initiative. He has served as a member of the steering committee of the Singapore chapter of the International Game Developers Association (IGDA) and worked closely with Singapore game developers to launch industry-wide initiatives and administer content development grants as an assistant manager in the Media Development Authority (MDA) of Singapore. Before 2005, he produced and designed PC online games at The Education Arcade, a research group at the Massachusetts Institute of Technology that studied and created educational games. He complements a Master’s degree in Comparative Media Studies with work in Boston’s School of Museum of Fine Arts, the MIT Media Institute, and the Singapore-MIT GAMBIT Game Lab, where he worked to help design both touchscreen and virtual reality-based games for student learning.
Lab, WMBR 88.1FM and the MIT Assassins’ Guild, the latter awarding him the title of “Master Assassin” for his live-action roleplaying game designs. He also founded a DJ crew at MIT.

Richard (Rik) Eberhart as Studio Manager for the MIT Game Lab, He spends his days playing Tetris: with people, boxes, tasklists, equipment, money, and time. When not staring at a spreadsheet trying to fit in another computer purchase, a last minute event budget, or placing undergraduate researchers on a Game Lab project, he’s chipping away at spreadsheets on his DS, reproducing pixel-art in Picross and Picross 3D, or managing the ultimate spreadsheet, a game of Sid Meier’s Civilization. He is also an instructor for two MIT Game Lab classes on game production and has served as a mentor and director for multiple game development projects including elude, a game about depression produced in the summer of 2010. He holds a Bachelor of Arts degree from the College of William & Mary, is a Certified Scrum Master, a PMI Agile Certified Practitioner, and is currently working towards a Serious Games MA Certificate from Michigan State University.

Eric Klopfer is Professor and Director of the Scheller Teacher Education Program and The Education Arcade at MIT. He is also a co-faculty director for MIT’s J-WEL World Education Lab. His work uses a Design Based Research methodology to span the educational technology ecosystem, from design and development of new technologies to professional development and implementation. Much of Klopfer’s research has focused on computer games and simulations for building understanding of science, technology, engineering and mathematics. He is the co-author of the books, Adventures in Modeling, The More We Know, and the recently released Resonant Games as well as author of Augmented Learning. His lab has produced software (from casual mobile games to the MMO The Radix Endeavor) and platforms (including StarLogo Nova and Taleblazer) used by millions of people, as well as online courses that have reached hundreds of thousands. His work has been funded by federal agencies including NIH, NSF and the Department of Education, as well as the Gates Foundation, the Hewlett Foundation, and the Tata Trusts. Klopfer is also the co-founder and past President of the non-profit Learning Games Network (www.learninggamesnetwork.org).

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Appendix

User Testing Feedback Form (June 2018 Version)

Pre-testing Questions (These questions were asked before the playtesting experienced, and involved a simple sit-down interview with the user tester.)

Name(s):
You (VR user) are a(n):

- Middle/High School Teacher
- Middle/High School Student
- High School Student
- Undergraduate student
- Graduate student (Masters/PhD)
- Researcher/Scientist
- Other:

You (tablet user) are a(n):

- Undergraduate student
- Graduate student (Masters/PhD)
- High School Student
- Researcher/Scientist
- Middle/High School Teacher
- Middle/High School Student
- Other:

Have you used VR before? If so, what did you do/what did you play?
(If used VR before) Have you used collaborative or multiplayer VR before? If so, what did you do/what did you play?
What is the relationship between you and your partner? How well do you know each other?

- Don’t know each other
- Know each other somewhat (acquaintances)
- Know each other very well
- Other:

[Internal] Did they make any comments about the narrative? (Note: “Internal” henceforth refers to inquiries or observations that were not asked of the user, but were recorded by team members to analyze user behavior.)

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VR questions – during gameplay

[Internal] About how long did the player use to finish the tutorial?
[Internal] What is the player doing during the time between tutorial instructions?
[Internal] Are there any signs of impatience or enjoyment during the tutorial? Ex. sigh, “this is so long,” trying to skip ahead or “Wow,” “cool,” “I know how to do ___ now!”

Once the user has had some time in the headset, ask the following questions. How does the headset feel? How do you feel using the hand controllers?
Now that you’re in the VR environment, is it different from what you expected? If so, how?
How do you feel about moving through the environment? Do you feel nauseous at all?
[Internal] What features did the player not use, or have trouble with during the gameplay? (Choices: Right hand to select, Left hand to see clipboard, Point and press button to move)
[Internal] How do they act when they communicate? Are they calm, frustrated, …

After Tutorial: Ask the player what they think the goal of the game is. Also ask them how they can complete that goal. Write their response below.

Tablet questions – during gameplay

[Internal] About how long did the player use to reach the midway (“Explore around!” or “Your partner has joined …” instruction) of the tutorial? The end of the tutorial? (Please time the player.)
[Internal] Write down some observations while the player is doing the tutorial. Are they trying out the action after each tooltip?
[Internal] Are there any signs of impatience or enjoyment during the tutorial? Ex. sigh, trying to skip ahead, “this is so long,” or “Wow,” “cool,” “I know how to do ___ now!”

After Tutorial: Ask the player what they think the goal of the game is. Also ask them how they can complete that goal. Write their response below.

After some time, ask the following questions. How do you feel about the controls?
How intuitive do you find the UI? Do things respond as expected?
Is there a tool or function not available that you wished you had?
[Internal] What features did the player not use, or have trouble with during the gameplay? (Choices: info mode, Beacon mode, Pinch to zoom, Rotate, Wheels, Beacon, Undo beacon, Reset, Clear, Disease information)
[Internal] Did the navigator finish the entire tutorial before the explorer or after the explorer?

Before:
After:
Other:

[Internal] How do they act when they communicate? Are they calm, frustrated, …

Post-Testing

Did you find the experience engaging? Why or why not?
Was the tutorial engaging? Why or why not?
Was the tutorial informative? Why or why not?

How do you feel about the tutorial instructions in general? What was confusing, if any? What was clear, if any? (Please include whether you were a VR or tablet player.)
Did you understand how to move and operate the touch controllers or tablet from the tutorial?
Did you understand what was the objective of the game from the tutorial? Any comments?
Did you understand that you had to work with your partner from the tutorial? Any comments?
Did you feel that you had too short, enough time, or too long to learn how to navigate in VR or on the tablet? (Please include whether you were a VR or tablet player.)
Did you feel that the narrative helped you understand the experience?
Did you feel that you learned anything new about cells from this experience? How does this differ from images of cells that you may have seen in school or in the media?
Was having a partner useful, or do you think that could you have done everything by yourself?
What kinds of information did you share with your partner? What cooperation was necessary to meet your objectives?
Is there anything you would have changed or added to the interaction? What could have enhanced the multiplayer experience? (Tools, features, …)