Creators, Classrooms, and Cells: Designing for the Benefits and Limitations of Learning in Immersive Virtual Reality

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Abstract

In the last few years, the perception of virtual reality (VR) has shifted from an entertaining novelty to an increasingly mainstream technological medium. However, the methods of creating and assessing high-fidelity immersive VR for learning remain nascent. With the growing demands for change in the 21st-century American education system, it is increasingly important for designers and developers to approach the topic of VR for K-12 learning thoughtfully yet critically.

This thesis grounds VR within the greater context of technology-mediated learning by examining its affordances, relevant educational frameworks, and cognitive limitations through the academic lenses of pedagogy, cognitive science, and educational psychology. It then utilizes a case study, the CLEVR project, to trace an in-depth example of an ongoing VR game through user feedback, data analysis, and iterative game design. Ultimately, I use findings generated from the CLEVR project to develop recommendations for designing and integrating VR into K-12 classrooms, with the hopes of informing current and future designers about balancing VR's affordances with learning outcomes in order to develop successful immersive learning experiences.

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Introduction

The objective of this thesis is to analyze and better comprehend the learning affordances of virtual reality through iterative game design that can be applied to K-12 classroom settings. While I do bring in examples of previous and ongoing VR projects by other researchers, I focus the bulk of my analysis on a project called CLEVR (Collaborative Learning Environments in Virtual Reality) which I have been a part of research and development for the last few years. CLEVR's product, an immersive VR game named *Cellverse*, is an interactive experience designed to help high school- and college-aged players learn cellular biology through VR-mediated exploration. Throughout the entire manuscript, I address the following questions:

- What affordances contained within VR technology allow for fruitful learner-centered interactions with educational content?
- What does it take to design, develop, and iterate upon a VR-mediated learning experience for K-12 classrooms?
- What forms of learning are most well-suited for VR?
- How does CLEVR confront or reflect established understandings about VR's usefulness in learning?

This manuscript is intended for VR-interested persons and designers of all experience levels. In particular, this is a learning tool for future designers new to or unfamiliar with educational research. I hope that this offers a valuable insight into the variability and "messiness" commonplace in learning design, particularly in context of the uncertainties of newly mainstream and thus largely untested technologies. To be at the forefront of researching VR for school-based learning applications is both unnerving and exhilarating, and may pave the path for more interactive, immersive technologies to be effectively harnessed within classrooms.

Designing effective VR-based learning experiences lies at the nexus of theories and frameworks eclipsing education, game design, and cognitive science. More than anything, such design requires balance. This thesis demonstrates that what proves an effective VR experience in the eyes of seasoned game designers may prove unproductive in a K-12 setting. In sharing these findings, I aim to offer a thoughtful insight into what it takes to design a VR experience that is engaging without being overwhelming and is both entertaining and informative.

The Organization of This Thesis

Chapter One reflects on the history and influences of VR and touches upon the technological shifts in K-12 learning in the 21st century, as well as the status of technology-mediated learning in schools.

Chapter Two discusses the major affordances that define VR, gradually narrowing down to VR's relevant learning affordances. It will provide an overview of relevant VR-centric learning theories, as well as discuss the cognitive limitations of VR.

Chapter Three centers the critical discussion of VR-mediated learning around a case study, the CLEVR project. It details the design of the project between 2017 to 2020 with an emphasis on the design and user testing analysis between Fall of 2019 and Spring of 2020. The chapter focuses on how learning has been scaffolded within and outside of the experience, and how learning was adjusted (and could continue to be adjusted) to account for the most optimal forms of learning that take place within VR.

Chapter Four analyzes the results of the CLEVR project through the lens of the affordances and frameworks mentioned in Chapter Two. It then reflects upon the design process of CLEVR, how user feedback shaped the trajectory of the design process and provides guidelines and suggestions for how future learning designers can iteratively develop and balance effective VR learning experiences for K-12 education.

Chapter One: Understanding the Origins and Affordances of VR and Its Potential Role in Education

When discussing the emergence of any technological form in history, scholars may point to any number of "defining moments" that are imprinted within living memory. While some moments capture the human imagination – "Mr. Watson, come here, I want to see you" – not all of them are dazzling, memorable, or even agreeable. These moments, however, shape how society perceives technology and how the technology may be utilized for years to come.

We shall now pivot our attention to immersive, technology-mediated, and fully simulated experiences, better known as *virtual reality* or *VR*. Virtual reality's most recent "defining moment" came from the annual TED conference in Vancouver, Canada. In 2015, visual artist and technologist Chris Milk stood in front of a crowd of hundreds and proclaimed VR as the "ultimate empathy machine." Through recordings of 360-degree camera captures of wide-eyed Syrian refugee children, Milk demonstrated his now-infamous VR film, *Clouds Over Sidra.* He wrapped up his ten-minute talk with the proclamation that VR technology "connects humans to other humans in a profound way." The electric moment of virtual connection – the user arriving face-to-face with another person they may otherwise never have an opportunity to meet – is how, he concluded, "virtual reality has the power to actually change the world." Milk's words were met with a standing ovation from the audience and was promptly echoed by numerous media sources across the planet. [1][2][3]

Five years after Milk's legendary presentation, can we conclude that virtual reality has changed the world? VR's usages currently run the gamut from multiplayer games to surgical simulations, but the technology itself remains challenging to develop for and harder to financially access for much of the world's population. Proponents may believe that it has truly connected people across borders and changed the world for the better, while skeptics may dismiss Milk's "empathy machine" as technocentric idealism. The truth, as it often does, lies somewhere near the middle. Much like facial recognition technology or autonomous driving vehicles, virtual reality has ridden the wave of media-generated hype that has carried every generation of emerging technology before it. As the hype has gradually dissolved and VR's presence has grown more pervasive in mainstream society, we as creators and consumers have begun to uncover its many advantages and disadvantages. Studying these technological applications without distraction from a glitzy veneer of publicity is essential to determining whether VR is well suited for developing empathy, and where else it may be beneficial in our lives.

This chapter will first introduce the historical groundworks of VR, establishing it as a technology with a basis in 20th-century technological innovations and pre-20th century

[1] R.L. Adams, "Five Ways Virtual Reality Will Change the World," *Forbes*, October 17, 2016, https://www.forbes.com/sites/robertadams/2016/10/17/5-ways-virtual-reality-will-change-the-world/#3ff451f62b01.
[2] Joel Stein, "Why Virtual Reality Is About to Change the World," *Time*, August 6, 2015, http://time.com/3987022/why-virtual-reality-is-about-to-change-the-world/.
[3] Madhumita Murgia, "How virtual reality is going to change our lives," *The Telegraph*, December 12, 2015.

experiments in transportive environments. Then, the chapter will focus on the role of VR in the context of learning to frame the arc of this thesis.

VR and Other Unrealities

In this era of constant innovation, it is common for technologists to throw about multiple terms that all evoke different technology-mediated aspects of unreality. Three major terms stand out: *virtual reality* (VR), *mixed reality* (MR/XR), and *augmented reality* (AR). While only VR is immediately relevant to this thesis, it is useful to understand the differences among these unrealities for future reference.

Paul Milgram and Fumio Kishino first defined and visualized the "virtuality continuum" in their 1994 paper "A Taxonomy of Mixed Reality Visual Displays," which continues to inform our understanding of the reality-virtuality "spectrum" (Figure 1). The relevant terms are defined as follows:

- *Virtual reality* (ascribed to the *virtual environment* in Fig 1) is entirely simulated. The entire environment – what the user sees, hears, and experiences – is virtual.
- *Augmented reality* is grounded in the "real" world and contains virtual objects that are overlaid and spatially registered to the user's surrounding environment. A virtual block, for example, could be mapped to a real-world table. *Augmented Virtuality* (Fig 1) is the opposite – it is grounded in the virtual world and contains "real" objects registered to the virtual environment.

- *Mixed reality* utilizes technology to blend the real and virtual worlds to a greater degree than AR. On the reality-virtuality spectrum, they span the wide gap between VR and AR.

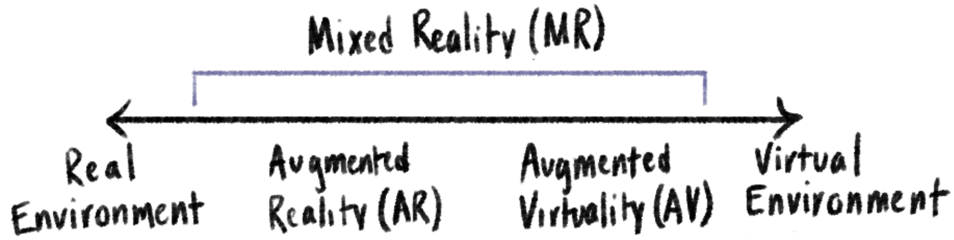

Fig 1: A visualization of Milgram and Kishino's virtuality continuum (Milgram & Kushino, 1994).

Historical Precedents of VR

Tracing the emergence of VR requires an understanding of the technology that was first developed to visualize it. VR first emerged as a technological form in the mid-20th century when American computer scientist Ivan Sutherland envisioned an "ultimate display" where computers could "control the existence of matter." He proposed that computers would not simply display realistic images but be able to generate actions that impacted the real world. (A virtual fruit, for example, might be picked up and eaten. A virtual bullet would be capable of killing; this, thankfully, has not yet come to fruition.) Three years after his groundbreaking 1965 paper, he and his student Bob Sproull developed a virtual head-mounted display (HMD)[4], nicknamed the "Sword of Damocles," at the MIT Lincoln Laboratory. A spiritual ancestor of the modern virtual reality headset, the Sword of Damocles allowed users to gaze into simple computer-generated 3D images superimposed over the real world. This HMD was mounted to the ceiling and was so threateningly massive that users coined its nickname out of fear of it crashing down upon their heads. Although the technology was primitive compared to the HMD's high-powered descendants, the Sword of Damocles successfully demonstrated early iterations of head-tracking techniques that monitored and responded to the position of the user's head in virtual space.

Sutherland's contemporary, computer artist Myron Kreuger, exhibited a series of computer-generated environments that consisted of projectors, cameras, and sensors displaying images onto flat surfaces. These "responsive environments" physically surrounded viewers and were capable of real-time responses to their movements and actions. Kreuger referred to his projects, unencumbered by headsets, as "artificial realities" – their descendants are now known as cave automatic virtual environments (CAVEs). Despite their groundbreaking research in the area, neither Kreuger nor Sutherland pioneered the words "virtual reality." It would take until 1987 before the term was coined by artist and scientist Jaron Lanier, co-developer of one of the first commercial VR headsets at his company VPL Research. Rolled out in 1990, VPL Research's "EyePhone" sold for a

[4] While many publications claim that the Sword of Damocles was the first HMD, I cannot verify that claim. The first HMD design, coined the "Telesphere Mask," was patented by cinematographer and VR pioneer Morton Heilig in 1960. Although the Telesphere Mask appears remarkably similar to modern HMDs like the Samsung Gear or Oculus Rift, it was never built and remains relatively unknown compared to the Sword of Damocles. Heilig was also the inventor of the infamous 1962 "Sensorama," a groundbreaking immersive multimedia machine considered an early VR experience.

staggering $9,000[5] at the time of release and was offered alongside a set of haptic (touch-responsive) gloves, also selling for $9,000.

The 1980s and 1990s marked a growing interest in using immersive VR for video gaming. Although several attempts were made by gaming companies like Sega to introduce HMDs to commercial markets, they failed due to high costs and technical limitations (Horowitz, 2004). VR did not see success as a mainstream medium until the public announcement of the Oculus Rift headset in 2014. Unlike its predecessors, the Rift was smaller, lighter, and far more portable. Interest in the technology pushed its initial Kickstarter campaign $2,400,000+ over its initial $250,000 goal.[6] Acquisition of the Oculus company by social media giant Facebook, Inc. – and Facebook's subsequent aggressive marketing of the $599 headset – further spurred the ambitions of media companies to make virtual reality a ubiquitous household presence. With the proliferation of competing headsets like the HTC Vive or the Sony PlayStation VR, the technology has certainly become more ubiquitous. Sony, the largest manufacturer, sold 2.2 million headset units in 2019 alone – Oculus and HTC sold 1.7 million and 0.8 million, respectively (Statista Research Department, 2020). Alongside the hardware, VR software has proliferated in recent years. Software market size is expected to reach $3.1 billion in 2020 and an estimated $6.4 billion in 2022 (Liu, 2019).

[5] According to the Bureau of Labor Statistics, the 1987 EyePhone would cost about $20,800 in today's money. Compare this to the $599 price of the first Oculus Rift headset released in 2016.
[6] The original Kickstarter campaign remains at this link: https://www.kickstarter.com/projects/1523379957/oculus-rift-step-into-the-game

While the technology supporting VR is incredibly modern, the concept is far from new. Scholars and journalists alike point to 19th-century Euro-American inventions as the technological predecessors of virtual reality, henceforth grouped under the general umbrella of *unreality*.[7] Most apparent are binocular-shaped stereoscopic viewers that presented users with interchangeable views of distant lands, and 360-degree panoramic paintings that surrounded viewers with vivid scenes of landscapes and historical battles. The design principles of these objects continue to inform modern VR technologies such as 360-degree video and mobile phone-based HMDs. Furthermore, stereoscopic visualizations continue to be used as learning tools in science and mathematics.

However, the desire to relocate oneself into a different world through environmental manipulation is far more ancient and spans a wider geographic range than one might assume. Eighteenth-century European nobility festooned entire rooms with richly decorated furniture and frescoes of the Rococo movement, transforming utilitarian interior spaces into escapist pastoral worlds. Thirteenth-century Japanese Buddhists constructed Zen gardens that carefully reformed nature into harmonious constructs of inner peace. Archeologists uncovering Malta's 6,000-year-old Hal Saflieni Hypogeum discovered that chanting within a specific room inside the building produced a powerful acoustic resonance, creating a chilling yet relaxing sensation in listeners described as "a different state of consciousness."[8]

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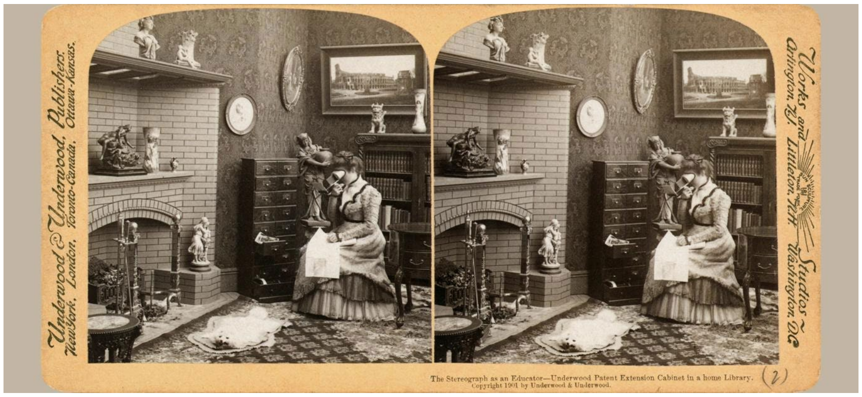
[7] As virtual reality inherently implies a computer-simulated environment, pre-digital technologies will be henceforth referred to as *unreality* – an environment and/or experience whose inherent construction is meant to transport a visitor out of their day-to-day reality and into a foreign, historic, or fantastic world.
[8] For more academic research on the Hal Saflieni Hypogeum's acoustic properties, see Debertolis, Prof.agg & Coimbra, Fernando & Eneix, Linda. (2015). Archaeoacoustic Analysis of the Hal Saflieni Hypogeum in Malta. Journal of Anthropology and Archaeology. 3. 10.15640/jaa.v3n1a4.

Why does it matter that we also ground unreality in non-panoramic, non-stereoscopic experiences? Both stereoscopic viewers and panoramic paintings were navigational with a clear input-output (Figure 2). The primary mode of interaction was through an unstable form of "looking" – stereoscope viewers would be forced to break immersion to switch cards. Panorama viewers could move within a constrained physical space to view the artwork, but otherwise had few other modes of communication. The examples given above suggest that unreality existed for reasons beyond the simple pleasure of looking. Within these augmented spaces, people created new forms of meaning for dancing, socializing, meditation, or prayer. Throughout history, people have sought to transport themselves out of reality for obtaining joy, escaping pain, pursuing spiritual enlightenment, or simply for discovering new information in a novel manner. VR researchers and designers should not ignore these precedents. There are numerous forms of interaction elements that may exist in VR, unbound by the physical world and able to produce totally unique experiences.



(Figure 2: A 1901 photograph of a young woman using a stereoscope. The cabinet on the far right is filled with stereographs. From the Library of Congress.)

Learning in VR and the Modern Classroom

Several VR-based learning experiences have already taken advantage of the "unbound" affordances of the technology. VR, as will be discussed, has powerful educational potential. Because it can allow users to experience and iterate upon difficult, dangerous, or high-stakes scenarios without fear of real consequences (Slater & Sanchez-Vives, 2016), VR-based learning experiences are often designed for job training purposes. The U.S. military has developed VR-based synthetic training environments (STEs) to prepare soldiers for various combat and rescue operations, replacing costly real-time training facilities.[9] Airline pilots have trained on flight simulators for many decades; VR allows them to repeatedly practice emergency maneuvers in simulated conditions without the risk of endangering their lives inside a real cockpit (Prokopovič, 2019). Similarly, hospitals and medical schools are increasingly adopting immersive VR to allow doctors to practice difficult surgical procedures without the risk of harming a real patient (Zaleski, 2019). While technology-mediated simulations may never entirely replace "real-life" on-the-job experience, VR-based training can certainly help prepare professionals for any number of emergency scenarios.

How could VR be incorporated into K-12 learning? Can VR teach chemistry lab safety to a middle schooler as effectively as it can teach a pilot-in-training how to handle a rough landing? While lab safety may seem like a far cry from emergency training, the previous examples reflect how learning-based VR makes up just one contingent of

[9] "Synthetic Training Environment (STE) White Paper." United States Army Combined Arms Center. https://usacac.army.mil/sites/default/files/documents/cact/STE_White_Paper.pdf.

constructivist learning experiences. The groundworks that have guided the creation of 21st-century interactive games, simulations, and other playful experiences lie upon psychologist Jean Piaget's (1896-1980) theory of constructivism, which posits that learning and meaning-making is driven by experience. Piaget's frameworks were expanded upon by progressive educators like John Dewey (1859-1952), who proposed that education be grounded in "sustained inquiry" (Dewey, 1916). The idea is straightforward in theory: authentic, grounded interactions with the world relevant to the knowledge that learners are expected to understand help build experience. Many teaching methodologies, including scientist and educator Maria Montessori's (1870-1952) internationally famous "Montessori Method of Education," have been founded upon constructivist philosophy. Virtual reality, which involves a physical body moving within and interacting within virtual 3D space, is a technological form that truly embodies constructivism.

Much ongoing pedagogical research (including that of VR) roots itself in Piaget's constructivist philosophy and related educational frameworks. However, although constructivism informs much of the mindset behind modern educational technology development, it is not the most prominent educational theory that drives VR design. Other learning forms, such as situated learning, embodied learning, and experiential learning, are all enveloped by VR. These will be discussed in further detail in Chapter Two.

Challenges in Technology Adoption in K-12 Classrooms

While more school systems than ever have adopted constructivist methods in the last few decades, the vast majority continue to rely on “traditionalist” methods – one-sided lectures and rote memorization of standardized educational concepts – to push children through school and graduation. Moreover, new technologies are not simply financially taxing, but difficult to integrate into preexisting curricula. When schools do adopt new technologies, much of the pressure of learning, implementing, and integrating the technologies falls onto teachers. This can be a difficult position, especially when teachers do not have the time, money, or capacity to do so.

Teacher adoption of new technologies is a crucial hinge upon which educational innovation pivots, but researchers disagree on how to introduce technology to educators of different skill and familiarity levels. There are two general perspectives regarding teacher approaches to adopting new practices: the essentialist model and the development model. The essentialist model posits that teachers exist on an inflexible scale of stances towards technology and practice, ranging from progressive “innovators” to old-fashioned “laggards” (Rogers, 2003). Conversely, the developmental model suggests that teachers are learners and progress through new technology adoption at varying rates (Dwyer, Ringstaff, & Sandholtz, 1991). In this thesis, I use the philosophy of the developmental model to consider how VR designers can meet teachers along their developmental trajectories to show how VR can be thoughtfully used in teaching.

Debates over teaching methodology, while relevant, are not a new development; educational policymakers in the U.S. have debated school reform for many decades. The reasons for such systematic inertia are too complex and numerous to list in full: lack of finances, lack of teacher training, stubborn school systems or administrators, and pressure on teachers to ensure that students pass state-mandated assessments are a few of a variety of factors that impede change.[10] The current educational system is, unfortunately, not one that will be able to adequately prepare students for the post-graduation future. In 2012, the U.S. National Research Council published a report titled *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century.* The skills that they identify as being vital for living in the modern era include flexibility, creativity, initiative, innovation, intellectual openness, collaboration, leadership, and conflict resolution. These skills will be critical for graduating students entering a tumultuous and diversified global society but are not well prioritized by the current schooling system of many American states. A thorough web search of the U.S. Common Core State Standards reveals just how sparingly these "21st-century skills" are integrated. Six of the eight skills are never referenced in terms of student learning. "Creativity" is mentioned once in the high school math modeling curriculum; only "collaboration" is mentioned more than five times, all within the primary and secondary English and Language Arts standards.[11]

These observations are disheartening but should not be discouraging. Educational VR remains a nascent but growing field and may help provide the means to simultaneously

[10] Perhaps the best resource for discussing this complex topic is David Tyack and Larry Cuban's *Tinkering Towards Utopia* (Harvard University Press, 1995).
[11] These observations were taken from a comprehensive web search of the Common Core site at http://www.corestandards.org/ between January and March of 2020.

address traditional curriculum requirements and develop 21st-century skills. Low-fidelity HMDs like the Google Cardboard are built to be widely affordable and, when paired with ubiquitous mobile devices, allow classrooms to participate in “virtual field trips” (Google for Education). In terms of research, modern pedagogical (teaching methodology) researchers have been active in studying VR and its potential benefits for student learning. Drawing from a rich literature of educational research, they have explored the potentialities and applications of VR and its role in augmenting – and sometimes overwhelming – human cognition.

STEM (Science, Technology, Engineering, and Mathematics) education has become a particularly fertile ground for VR design and development. Various science-based projects have been shown to improve high school students' understandings in abstract microbiology concepts (Tan & Waugh, 2014); to improve middle school students’ understanding of molecular structures (Chiu, Dejaegher, & Chao, 2015); and to enable interactive virtual laboratories (Potkonjak et al., 2016). Studying VR in context to learning has allowed researchers to better understand how human cognition can be augmented with – and overwhelmed by – technology-based media. These VR projects and more will be analyzed in Chapter Two, which will highlight several preexisting examples of VR-mediated science learning experiences.

Grounding VR-based Learning in Modern Education

Learning institutions are infamously slow to integrate technology. However, in this rapid-fire digital age, many school systems have raced to catch up with the ever-diversifying gadgets and programs that students use every day. Educational technology (edtech) spending, reflecting public demand for edtech, has skyrocketed in recent years. In 2015-16, schools in the United States spent $4.9 billion on laptops, desktops, and touchscreen tablets and a staggering $8.3 billion on corresponding educational software and digital content.[12] While these statistics prove there is a burgeoning market (and, simultaneously, growing interest) for edtech, the question of *how* to properly use such technology remains up for debate.

To explain the ongoing successes and failures of evaluating technology-mediated learning would be a Herculean task; therefore, I will point to a relatively new report to comprehensively summarize these findings. A 2019 report from the MIT Abdul Latif Jameel Poverty Action Lab (J-PAL), analyzed the results of 126 evaluations on online courses, computer-assisted learning, social psychology programs, and other edtech formats. Ultimately, much of the ongoing research reveals that edtech has the potential to offer improved academic outcomes – but under specific conditions. For example, Alpert et al. (2016) found that students taking online-only classes gained convenience but lost the face-to-face contact ubiquitous in physical learning settings, which reflected in lower overall learning outcomes. These studies revealed that technology can augment but not replace

[12] Singer, Natasha. Amazon Unveils Online Education Service for Teachers. *The New York Times*, 27 June 2016, www.nytimes.com/2016/06/28/technology/amazon-unveils-online-education-service-for-teachers.html.

traditional learning formats; in other words, one cannot improve learning outcomes simply by reformatting a paper test on a computer screen. The J-PAL study concluded that more research is needed to "explore the potential role of education technology in schools, identify interventions that expand opportunity, and evaluate how underlying mechanisms can advance learning."[13] While VR was not a topic of focus in the J-PAL study, we can and should evaluate it using the same standards in order to understand its potential role(s) in the future of learning.

There remain numerous questions to be addressed: In what ways can VR best promote student learning and support learning objectives? What forms of interaction and meaning-making within VR can inform different aspects of learning? Once the thrill of using a fun new technology like VR for the first time – the so-called "novelty effect" – wears off, what is left to keep students interested and engaged? On the side of the designer, how do we account for learning in VR? Most of all, how do we measure learning in the sheer mutability and diversity of the modern classroom? If teachers are given appropriate and adequate tools, materials, and support for VR, they will be able to develop skills and strategies for effectively incorporating VR into their classes. However, introducing emerging media technologies into classrooms and integrating them into school curricula is far easier said than done. As previously stated, current schools are often woefully under-equipped to handle VR, lacking the time, financial resources, and technical knowledge to do so. A skeptic may thus ask: if the technology is still so expensive, and the public education

[13] MIT Abdul Latif Jameel Poverty Action Lab, https://www.povertyactionlab.org/sites/default/files/documents/education-technology-evidence-review.pdf.

system still prioritizes standardized test results over 21st-century skills, then why even bother considering how VR can augment K-12 and college-age learning?

My response is simple: we cannot wait for the technology to become mainstream before we can begin thinking of ways to effectively design for it, nor can we wait for constructivism to become a mainstream pedagogical philosophy before thinking of ways to integrate relevant technologies into schools. We must examine how VR can be used (or misused) before it becomes available to a wider audience. Moreover, high-fidelity VR may not remain so expensive in the oncoming years; consider how the Oculus Rift, which cost $549 upon launch in 2017, now costs $399 in its newest iteration.[14] Smartphones and laptops, once unaffordable emerging technologies themselves, are now ubiquitous in schools across the country.

Throughout this manuscript, I wish to address two questions: Why VR? And why *not* VR? When spending money and time to integrate emerging media into class curricula, it is essential for designers and educators alike to understand the points at which VR can produce successful learning, and when it could be best avoided. At such an early stage of understanding, both failure and success in experimentation can offer us valuable lessons for posterity.

[14] Several technology news sources from 2016 confirm that the Oculus Rift headset cost $599 or $600 at launch: for example, see https://www.vox.com/2016/1/6/11588532/the-price-for-the-oculus-rift-virtual-reality-headset-599. Note that it was not released with hand controllers, which were initially sold separately. Compare this to the $399 price of the Oculus Rift S listed currently listed on the company website: https://www.oculus.com/rift-s/.

Chapter Two: Understanding the Affordances of Interactive VR

In the previous chapter, I outlined the historical precedents of VR, emphasizing the potentialities for learning with VR. It is vital to analyze VR's unique *affordances*, or inherent properties to understand how it can be implemented most effectively. These affordances are closely interrelated. In "General Affordances of VR," I will provide an overview of VR's most discussed affordances – presence, immersion, embodiment, and interactivity. In the following section "Learning Affordances of VR," I will shift to discussing affordances central to VR-augmented learning, which will accumulate much of the theoretical constructs developed by prominent scholars in education and cognitive science. As every technology has both affordances and limitations, I will discuss potential challenges to creating VR for learning in "Limitations to VR-Based Learning."

It is important to remember that the existing field of VR research remains nascent and decentralized. This chapter is not a comprehensive review of all pre-existing research; the goal is to introduce terminology, concepts, and recent research findings, and develop a conceptual framework for designing in VR. I will use this framework to discuss the case study of the CLEVR project.

Affordances of VR

Presence, Immersion, and Embodiment

Virtual reality is often defined by two unique affordances: *presence* and *embodiment*. Presence is the psychological feeling of "being there." Slater & Sanchez-Vives (2016) describe VR-based presence using two terms: "place illusion," the feeling of existing within the virtual environment despite the subconscious awareness that one is not actually present, and "plausibility," the illusion that events occurring in the virtual environment are actually happening. For example, a user watching the 360-degree documentary *Vulkane* may understand that they are not truly peering into the mouth of an active volcano, but the graphics are convincing enough so the user will still flinch backwards when molten lava seemingly spews in their direction.

Presence overlaps with the term *immersion* (Slater & Wilbur, 1997). Dede et al. (2017) argue that immersion is essential to motivation and learning in VR. Where presence reflects psychological feeling, immersion may be construed as the technological or practical application that creates presence. Slater (2016) suggests that the more seamless the underlying technology, the more potential for immersion that exists – this is encapsulated in the various levels of technological sophistication that exist in modern VR headsets, known as "degrees of freedom."[15] Headsets with three degrees of freedom like the Google Cardboard can track horizontal and vertical head movement and head tilt. Headsets with six degrees of freedom like the Oculus Rift or HTC Vive also track body position and movement , allowing for the system to account for a user's movement forwards and backwards, from side to side, and upwards and downwards. Headsets with more degrees of freedom allow for higher immersion by evoking a stronger psychological sense of presence in the user. This claim is further supported by Cummings & Bailenson (2015), who reviewed over 80 VR studies and noted the significant positive correlation between the

[15] For more detailed information on degrees of freedom, see "A Quick Guide to Degrees of Freedom in Virtual Reality," Kei Studios, https://kei-studios.com/quick-guide-degrees-of-freedom-virtual-reality-vr/.

ability of a technological system to render a vivid virtual environment (immersion) and the psychological feeling of being present (presence).

Presence and immersion are closely intertwined with *embodiment*. “Embodiment” has several meanings: Kilteni et al. (2012) define it as the sensation of “being inside, having, and controlling” a body within a virtual environment, while Johnson-Glenberg (2018) suggests that embodiment is created by gestural manipulation of the environment using the virtual body. In either definition, presence is a precursor to embodiment. This chapter uses Kilteni et al’s (2012) definition to describe embodiment to explore the difference between interactivity and embodiment. Moreover, embodiment should not be confused with the embodied learning theory championed by some cognitive scientists. Embodied learning suggests that knowledge is cemented in memory through the body’s repeated interactions with the physical environment (Lindgren & Johnson-Glenberg, 2013), and will be discussed in further detail later in this chapter.

Interactivity

Contrary to presence, immersion, or embodiment, interactivity is a term that has proven difficult to define immediately. The *process* of interaction may be defined as the level of responsiveness the virtual environment provides to the user when the user presses a button, waves a hand, or moves within the response provided by the VR environment when the user when the VR environment is manipulated, the user is provided with some sort of response and mentally connects the response with their input – a pressed button, a waved hand, or some other form of interaction. The type of manipulation and the type of response varies greatly; there are many interactive modalities, some yet to be discovered, that can customize a VR experience. Bailenson et al. (2008) suggest three major dimensions of interactivity: technology-based, process-based, and user-based. These dimensions can be simplified as follows:

1. *Technology* creates interactivity through embedded data-tracking applications that monitor user actions.

2. *Process* creates interactivity by depicting how user-to-user or user-to-environment communication shapes the experience.

3. *Users* themselves create interactivity through their psychological perception of the environment and its changes.

Using a combination of these dimensions, we can define three "inputs" that can create "outputs" offering a sense of interactivity. Consider this in comparison to the example of a computer with a traditional desktop interface. While technology, process, and user variation may all factor into a computer-based experience, all forms of interaction will flow back and forth between the user, the keyboard and mouse, and the screen (Figure 3). The screen is the singular source of output, the keyboard and mouse are the only sources of input. Bailenson et al's dimensions show that interactions within VR can be far more complex and potentially overwhelming than a typical 2D monitor setup. VR users must simultaneously process visual, audio, and tactile output.

(Figure 3: Outputs of a traditional computer setup versus a hypothetical immersive VR setup.)

How, then, can we account for different levels of interactivity that might exist within any one experience? A 360 video might not have as many modes of environmental manipulation as a multiplayer game, but its immersive nature does create greater presence than a "normal," 2D video. Thus, instead of regulating video as a passive experience, 360 video simply exists on a lower level of interactivity. VR artist Michael Naimark, in attempting to group all forms of VR experiences, orders levels of interactivity as follows:[16]

1. *Rotational navigation,* where a user may only turn their head or body 360 degrees to examine their surroundings.

2. *Positional navigation,* where a user may move around their physical environment, in turn moving their virtual body throughout the VR

[16] Naimark, M. "VR Interactivity: Some Useful Distinctions." Medium, 22 Oct. 2016. medium.com/@michaelnaimark/vr-interactivity-59cd87ef9b6c.v.

environment. At this level, users still cannot affect anything other than themselves – Naimark describes them as "ghosts."

3. *Predetermined transformation*, which produces an "illusion of control" by presenting the user with sets of preprogrammed decisions not unlike a choose-your-own-adventure novel.

4. *Freeform transformation*, which can only exist within a fully simulated and modeled environment. Although it is by far the most difficult VR experience to design and produce, it has the greatest amount of interactive potential.

By distilling the multitudes of interactive modalities above, we may define "interactivity" as follows: Interactivity occurs when a user converses with a simulated environment or objects or avatars within the simulated environment, prompting changes in the simulated environment. A major subset of interactivity is *gesture*, where movement is interconnected with meaning. Gestures in VR can take multiple physical forms, ranging from clicking on-screen buttons to making sweeping physical limb movements, which in turn provoke sensory feedback from the virtual environment.[17] The formula is straightforward: the user perceives some need for response from the virtual environment, sends a command through physical input, then perceives the output as a new response from the same environment (Figure 4). All interactive movements are not gestures, however; gestures are in some way relevant to the learning at hand; pushing to simulate

[17] Popularized by Piaget's theory of child development, skills that involve both physical (motor) actions and sensory feedback are known as *sensorimotor* skills.

movement of an object, for example, or sweeping the arms to conduct an orchestra (Lindgren et al, 2016). Other gestural forms are concentrated in the movement of the hands and fingers. Johnson-Glenberg (2018) points to the intuitive qualities of VR hand controllers as conduits for natural gestures like pointing or waving, due to the technology's ability to sense body movement and relative position. Most high-end headset devices have the capability to show responsive hand-like avatars that are directly mapped to the user's real hands. Because users intuitively treat their avatars as parts of their real bodies (Meister et al., 2015), they learn to replicate gestures just as quickly.[18] In essence, gestures in immersive VR environments can help to reinforce presence.

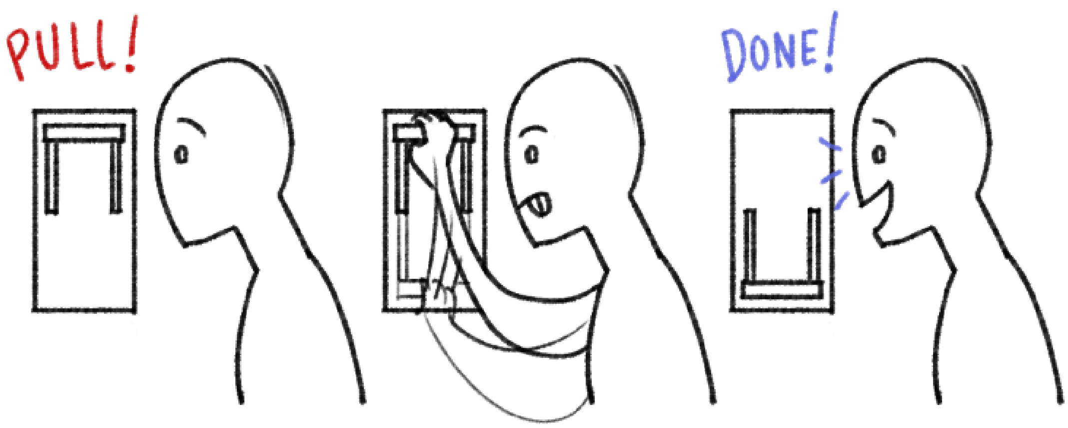


Figure 4: Author's drawing depicting the relationship between gesture and interaction.

Although I have discussed all these affordances separately, they should be viewed as closely intertwined entities. When one affordance increases or decreases in support or sophistication, others change accordingly. To best illustrate the interdependencies amongst the affordances, I have arranged them into the relationship diagram depicted in Figure 5. Note that certain affordances (presence, interactivity) are psychological in nature, and are

[18] This is an example of the notorious "rubber hand illusion" (Ehrsson, Spence, & Passingham, 2004).

intertwined with the technological affordances (immersion, gesture/movement) that create and support such feedback. All the affordances listed above factor into *embodiment*, which keeps the user feeling as though they are an observer and contributor of a dynamic virtual environment.

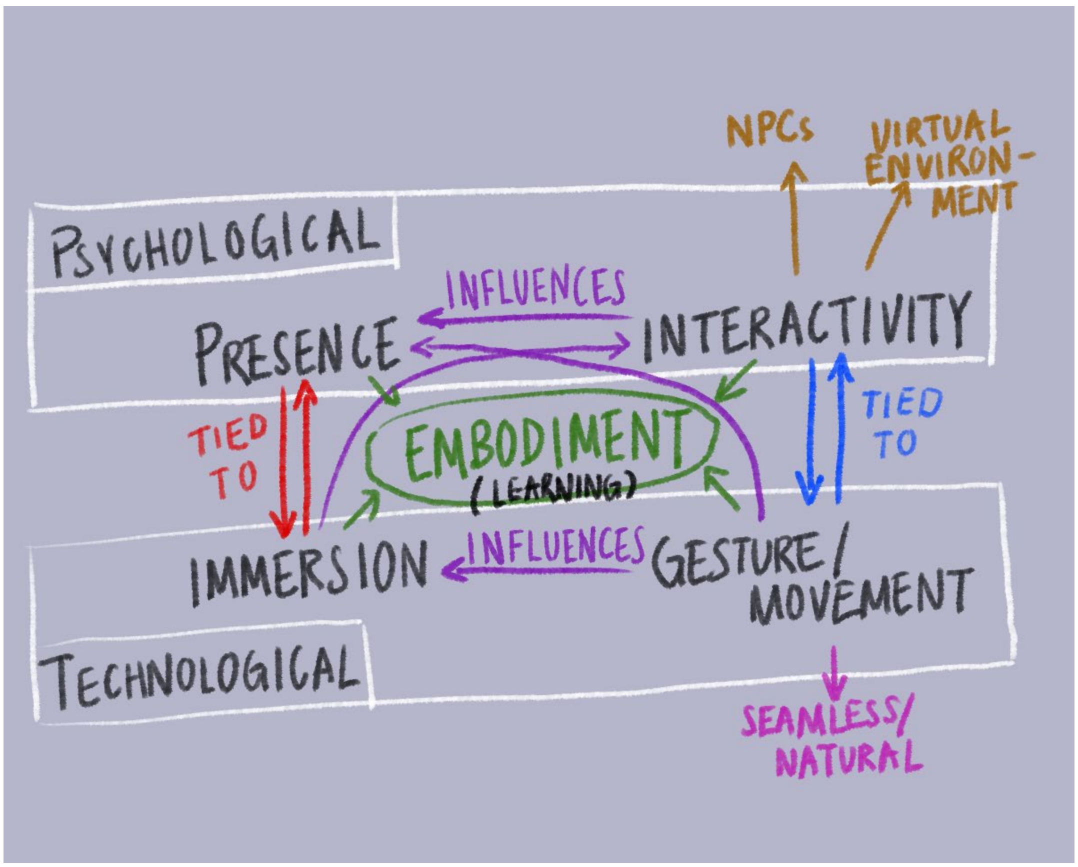


Figure 5: Diagram outlining the relationships among the major psychological and technology-mediated affordances of VR: presence, immersion, interactivity, gesture/movement, and how they contribute to embodiment.

Learning Affordances for VR

The previous section outlined the major general affordances in high-level VR experiences. Understanding the design of VR-based learning requires consideration of several other affordances that set VR technology apart from other media-based learning methods. To best organize the multitude of terms coming from disparate scholars and academic disciplines, I group them into two categories related to the process of pedagogical design: the *domain* (topics) and the *enabling learning theories*. These will both be discussed in further detail in the following pages.

Domain

Domain refers to the intended *topic of exploration* in any one VR experience. In terms of learning, domains can vary from traditional classroom subjects (arithmetic, science, language arts) to "21st-century skills" like collaboration or creativity. Hypothetically, VR can be used to explore all learning domains – but certainly, there are scenarios for which it is more useful than others. What is unique about VR that can be harnessed to optimize learning experiences?

In his book *Experience on Demand* (2018), Prof. Jeremy Bailenson suggests that VR should be reserved for anything "DICE":[19]

- *Dangerous*: may cause serious harm or death in a real-life scenario, e.g. jumping into an active volcano.

[19] Bailenson, *Experience on Demand*, p. 251-252.

- *Impossible*: unable to be accomplished in the real world, e.g. becoming a person of another race or gender.
- *Counterproductive*: achieving an experience or learning a lesson at severe personal cost, e.g. smoking a cigarette to learn about the dangers of smoking.
- *Expensive*: too pricey or rare for most people to achieve in real life, e.g. climbing Mount Everest.

Bailenson also emphasizes the consistent nature of VR, noting its ability to produce identical or near-identical experiences each time it is played. The digital nature of VR allows a user to practice scenarios that might be highly variable in real life, whether in preparation for a real-world task or in a rare-to-impossible situation. Decades of psychological studies have proved that *repetition* is a key factor in transferring knowledge (Wogan & Waters, 1959; Bromage & Mayer, 1986). Learners can try these VR experiences multiple times, allowing learners to transfer knowledge through repeated practice. It also offers great convenience at relatively low resource cost – all that is needed to enter another world, repeatedly, is to boot up a computer.

Dalgarno & Lee's (2010) work on virtual learning environments (VLEs) encompasses a wide range of technology-mediated 3D virtual environments, including VR. Their recommendations for VLEs remain relevant to immersive VR specifically in terms of domain possibilities, and parallel Bailenson et al's recommendations. The affordances are listed below:

> Affordance 1: Use [sic] VLE's to facilitate learning tasks that lead to the development of enhanced spatial knowledge representation of the explored domain.

Affordance 2: Use VLE's to facilitate experiential learning tasks that would be impractical or impossible to undertake in the real world.

Affordance 3: Use VLE's to facilitate learning tasks that lead to increased intrinsic motivation and engagement.

Affordance 4. Use VLE's to facilitate learning tasks that lead to improved transfer of knowledge and skills to real situations through real world contextualization of learning.

Affordance 5: Use VLE's to lead to richer and/or more effective collaborative learning as well as richer online identity construction and a greater sense of co-presence that will bring about more effective collaborative learning.

Johnson-Glenberg (2018) also highlights several suitable scenarios that VR is well-equipped to address. Modified from constructivist recommendations from an educational psychology textbook (Woolfolk, 2007), Johnson-Glenberg presents the following "common elements" where VR can positively augment learning. Contrary to Bailenson's emphasis on extreme scenarios, or Delgarno and Lee's comparatively surface-level recommendations, Johnson-Glenberg focuses on the potential use of VR for the personal betterment of the user and the user's perception of their social environment. They are listed as such:

1. Embed learning in complex, realistic, and relevant learning environments.
2. Provide social negotiation and shared responsibility.
3. Support multiple perspectives and multiple representations of content.

4. Knowledge is constructed (built upon)—the teaching approach should nurture the learner's self-awareness and understanding of ongoing construction.

5. Encourage ownership in learning.

Despite the differences in language, there are clear similarities among Dalgarno and Lee's, Johnson-Glenberg's, and Bailenson's suggestions. They all touch upon VR's ability to transmit "enriched" skills that, in turn, can be transferred to real-world scenarios. While these lists are not exhaustive, they provide an excellent starting point for understanding both what is possible and what is productive to put into immersive VR. However, within the realm of positive thinking lies a warning to designers: one should not simply rehash a conventional academic topic or port a flat screen experience to a 3D immersive environment without making serious changes to fit the technology. Bailenson (2018) warns against using VR for anything other than "the impossible," stating:

> "...don't waste the medium on the mundane. VR experiences should be engaged in mindfully… we should save [it] for the truly special moments." (Bailenson, 2018, p. 252-253)

Enabling Learning Theories

In Chapter One, I introduced Jean Piaget's philosophy of constructivism, which posits that "learning and meaning-making is driven by experience."[20] While constructivist

[20] See p.12 for a reminder of constructivism.

thinking is a keystone for many modern technology-mediated learning experiences, it is not the only theory that drives the development of VR for learning. In this section, I will provide an overview of three major learning theories that are most relevant to this thesis: experiential learning, situated learning, and embodied learning.

Experiential learning

Of the listed learning theories, *experiential learning* may have the closest resemblance to constructivism. Simply put, it is "learning by doing." Many of the things we humans learn outside of the classroom are gradually mastered through experiential learning, whether it be riding a bike or cooking a meal.

Experiential learning should not be confused with rote repetition – repetition does not account for experimentation, critical thinking, or potential failure. Kolb et al. (1999) define four major stages of an experiential learning experience, which are cyclical in nature. They are summarized as thus:

1. Abstract conceptualization: the user begins an experience with an abstracted set of knowledge and plans their course of action.
2. Active experimentation: the user executes their planned strategies and assesses the results.
3. Reflective observation: the user reflects on their experience and reviews their decisions.
4. Concrete experience: the user comes away with new or modified knowledge. As the user continues to learn, the experience cycles back to abstract conceptualization and begins anew.

Experiential learning in VR is generated through interactions between users and the virtual environment, which in turn allows users to construct their own experience (Jantijies et al. 2018). What potential does this hold for learning? Compared to a worksheet or textbook, VR offers responsive feedback more quickly, and in a more dynamic, interesting manner. Furthermore, the digital nature of VR software allows for repetition, experimentation, and reflection in a safe, low-stakes environment (Bailenson, 2018).

Situated learning

Dede et al. (2017) define *situated learning* as follows:

"'Situated' learning takes place in the same or a similar context to that in which it is later applied, and the setting itself fosters tacit skills through experience and modeling." (Dede et al., 2017, p. 6).

This definition insinuates that learning is best done when it is done *in context* to the real-world application. Dede et al. emphasize the process of *transfer*, applying knowledge learned in one situation to another. Situated learning is most successful when transfer between the "learning world" and the "real-world" closely resembles each other. The relationship between these two terms may seem obvious, but it grows increasingly complex as we consider the numerous forms of knowledge that can be transferred from a learning context into the real world. Bossard et al. (2008) further complicate the definition by splitting "transfer" into three different learning models: vertical or "low-road" transfer, where knowledge is transferred through the consecutive completion of similar tasks;

horizontal or “high-road” transfer, where the knowledge gained in one context is taken and applied to a new context; and “rich-road” transfer, where multiple forms of knowledge encoding are presented to a user at the same time, enriching the learning context. Rich-road transfer bears the closest resemblance to many immersive VR experiences. Bossard et al. (2008) highlight the example of VirtualDive (Popovici et al. 2005), a virtual environment that immerses children into a dynamic undersea landscape filled with AI-powered flora and fauna. VirtualDive utilizes “agent-based” virtual architecture that is capable of detecting changes within the environment and adjusting facets of the environment accordingly. As such, no two interactions are entirely similar. Children using VirtualDive make decisions based on the information provided – animal movement, climate, natural disasters, and so on. VirtualDive’s emphasis on dynamic decision-making demonstrates the possibilities of rich-road transfer.

With the multisensory qualities of VR, there is little wonder that so many VR experiences attempt to replicate the complexities of the real world. For example, “virtual laboratories” are a popular subject among game designers, as they allow users to iteratively practice essential laboratory skills in “lablike” virtual environments without wasting real-world resources (Chiu et al., 2015; Lindgren et al., 2016; Jang et al., 2017). A VR user practicing in a virtual laboratory with a virtual scalpel that can “cut” like an actual surgical tool would create knowledge that could – with practice – be transferred to a real-world medical environment. Proponents of the theory of situated learning would argue that the *presence* of being in the virtual environment, combined with the physical gesture of cutting with the scalpel, produces richer and more productive learning than if a user were to use the same tool in a 2D computer game (Dede et al., 2017).

Embodied learning

Embodied learning is closely related to *embodied cognition*; the former is a pedagogy-centric subset of the latter (Lindgren et al., 2016). Within the cognitive sciences, embodied cognition is a field of research “describing how our body and our environment are related to cognitive processes” (Skulmowski & Rey, 2018). Just as our minds influence our physical actions, physical actions can in turn influence our minds. The theory of embodied learning posits that physical action paired with educational objectives creates deeper learning (Kiefer & Trumpp, 2012). Cognitive scientists ascribing to embodied cognition theory argue that these two processes cannot be separated from each other, as they work together to create and disseminate the greater learning experience (Weisberg & Newcombe, 2017).

This theory has been well established in the field of education for many decades. In her 1936 book *The Secret of Childhood*, Maria Montessori first highlighted the positive correlation between mind and body development:

"Movement, or physical activity, is thus an essential factor in intellectual growth, which depends upon the impressions received from outside. Through movement we come in contact with external reality, and it is through these contacts that we eventually acquire even abstract ideas."[21]

The study of embodied learning as it relates to immersive technologies like VR remains quite novel. Embodied learning is fueled by physical methods of interactivity,

[21] Montessori, M. (1936). *The Secret of Childhood.* London: Longmans, Green.

specifically gestures.[22] Proponents of the theory argue that the multimodal nature of VR makes it an excellent conduit for embodied learning in 3D spaces (Dede et al., 2017; Johnson-Glenberg 2018; Thompson et al., 2018). When effectively incorporated into classroom instruction, a VR embodied experience can allow users to develop a "mental model" that facilitates information retrieval and thus creates deeper, more memorable learning (Dede et al. 2017). More technologically seamless or well-integrated VR experiences have the capacity to support deeper embodied learning activities.

Because of its reliance on physical movement, embodied learning theory is closely entangled with gesture. Gesture, when well-mapped to learning content, can promote memory retention when the user recalls information through doing the gesture (Johnson-Glenberg, 2018). Weisberg & Newcombe (2017) suggest that gesture can even *offload* cognition, freeing up mental resources for essential learning by storing extraneous or experimental information in movement. To better explain this claim, I will draw from their discussion of Kirsh & Maglio's (1994) *Tetris* study. Kirsh and Maglio noticed that *Tetris* players tended to perform excessive rotations and translations on their *Tetris* pieces while figuring out a puzzle. Although these actions appeared superfluous, Kirsh and Maglio argued that they allowed players to decrease the mental exertion of creating *Tetris* combinations by offloading cognition into the physical play environment. Being able to manipulate pieces on the computer screen was mentally less taxing than doing the same thing in their heads.

However, embodied learning only works properly, if the corresponding physical gesture is *congruent* or compatible to the learning at hand (Johnson-Glenberg, 2018).

[22] Recall my discussion of *gesture* in "Learning Affordances for VR."

Consider the physical skill of learning to ride a bicycle. Congruent gestures that facilitate learning the skill would involve the use of gripping the handlebars with the hands or pushing the pedals with the feet. Pushing the pedals with the hands, or swapping the bicycle with a horse, would be incongruent to the learning task at hand. When the gesture does not clearly match the task, Johnson-Glenberg postulates that the brain's sensorimotor areas are unable to connect the gesture with learning content.

Summarizing Learning Theories

Now that I have described each learning theory in detail, I will simplify them into the following working definitions for reference:

Experiential learning theory, or "learning by doing," posits that learning best occurs when users are given the opportunity to structure an iterative learning experience by forming a plan of action, executing the action, reflecting upon the results, and coming away with new or modified knowledge.

Situated learning theory, or "learning within context," posits that learning best occurs when the learning experience is as similar (and thus, transferrable) to the real-world application as possible.

Embodied learning theory, or "learning by moving," posits that learning best occurs when users connect educational objectives with compatible physical actions.

Limitations to VR-based Learning

Although the technology has been publicly available for at least five years at the time of writing, VR remains new to many people. Experiencing VR for the first time can be sensorially overwhelming yet exciting. A sudden uptick in learning performance upon introduction of a new technology, the notorious "novelty effect," is a familiar yet ephemeral phenomenon. However, ongoing learning cannot be sustained on the "wow factor" of VR alone. VR might be fun to play with the first one or two times it is introduced, but – as many designers will know – the initial thrill will eventually wear off. As Clark & Sugrue (1988) pointed out, learning gains from a newly introduced technological form gradually diminish as a user becomes more familiar with the technology in question. VR designers introducing an experience to prospective users should keep a vital question in mind: *Is the learning happening because the experience is effective, or because the technology is new and fun to play with?*

Aside from the novelty effect, what other limitations to learning in VR exist? The affordances (presence, immersion, embodiment, and interactivity) discussed in "General Affordances of VR" are crucial aspects of most sophisticated VR experiences for entertainment. Developers designing for a high-embodiment experience may find it logical to maximize all these affordances to produce the most engaging experience imaginable. While this may be a good mindset to have when producing a competitive and graphically intensive multiplayer game, does high embodiment produce good learning in an educational context? Some ongoing research suggests that increased technological sophistication may be counterproductive to achieving learning goals. The previous sections have outlined the affordances of VR in facilitating learning – this section will evaluate how learning can be complicated by the same affordances through Cognitive Load Theory and through the lens of the Cognitive Theory of Multimedia Learning.

Cognitive Load

Both cognitive scientists and our own lived experience suggest that humans have near-unlimited long-term memory but limited working (formerly known as "short-term") memory (Sweller, 1999). *Cognitive Load Theory* centers around the amount of working memory resources that a person can devote to a given task. Memory exertion can enter the human mind from multiple sensory channels: sight, sound, touch, and so on. The more sensory input that is activated within a given experience, the heavier the potential cognitive load. Cognitive Load Theory suggests that too much complex information being delivered too quickly can prove overwhelming, thus negating the possibility for learning retention.

Not all forms of cognitive load are created equal; in fact, not all cognitive load is "bad." In consideration of technology-mediated learning, Paas et al. (2003) divide cognitive load into three disparate forms:

1. *Intrinsic* or essential load is inherent to the learning material itself. It generally refers to the incoming visual and auditory input that the user consumes in preparation for mental processing.
2. *Extraneous* or ineffective load refers to information that imposes upon other cognitive load formats, consumes extraneous working memory resources, and ultimately does not contribute to learning. Note that extraneous load is

not necessarily "negative" load; Mayer et al. (2019) state that game design and medium of presentation is inherently tied to extraneous load.

3. *Generative*, germane, or effective load reflects on the user's ability to reflect on learning material and incorporate it within their own mental schema. The existing amount of generative load is dependent on the user's capability to organize and integrate information.

What are the implications of cognitive load for VR? Ideally, researchers should try to maximize intrinsic and generative cognitive load while minimizing unnecessary extraneous cognitive load. Such a recommendation is easier said than done. A cursory search of research articles comparing the learning effects of VR and non-VR learning experiences reveals that VR creates comparatively higher cognitive load among users, which in turn impedes memory recall and memorization (Parmar et al. 2016; Makransky et al. 2019; Roettl & Terlutter 2018). When comparing the ability of technology-mediated learning platforms in allowing users to consume and retain content knowledge, conventional 2D screens consistently outpace 3D VR interfaces because of the significantly lower sensory input (Figure AAAAA). Although students learning from a traditional curriculum may find VR more fun or more engaging than a computer screen – enjoyment is often unimpeded by cognitive load – they will learn considerably less than their computer-using peers unless cognitive load is evaluated carefully over the course of the learning design.

The Cognitive Theory of Multimedia Learning

Understanding Sweller's Cognitive Load Theory facilitates discussion of the Cognitive Theory of Multimedia Learning, which will be referred to throughout this thesis.

Introduced by educational psychologist Richard Mayer, the Cognitive Theory of Multimedia Learning (CTML for short) postulates that there are two main sensory channels for memory processing: visual (sight) and auditory (sound). These two input methods are processed separately by the mind and do not overlap with each other. Figure 6, which depicts the CTML process, shows that informational input is processed through a series of steps: filtering information, organizing it, integrating it into previous knowledge or schema, and finally processing it into long-term memory storage. Keeping in line with Cognitive Load Theory, CTML posits that when cognitive processing exceeds a user's mental capacity, "essential overload is experienced, inhibiting learning" (Meyer et. al 2019).

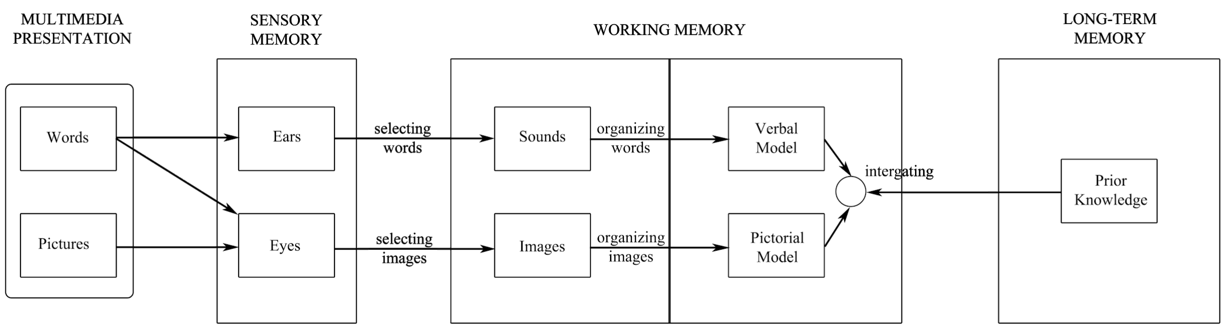


Figure 6: Mayer's Cognitive Theory of Multimedia Learning.

How does cognitive overload affect performance in a dVR task? Although Mayer and his colleagues acknowledge that VR is capable of generating high interest and motivation in users due to its immersive qualities, they argue that VR, compared to other technology-mediated learning formats, produces comparatively poorer learning outcomes due to lower knowledge gain (Moreno & Mayer, 2002).[23] To be specific, Mayer et al.'s research suggests that VR is a poor medium for imparting *declarative* or *factual knowledge*. Declarative knowledge is knowledge that is static or can be stored as facts. (This contrasts with *procedural* or "how-to" knowledge, which is knowledge utilized to carry out a task.)[24] Indeed, findings from ongoing cognitive science research in VR learning seem congruous with CTML; when users doing VR-based tasks were compared with users working on the same task on a non-immersive platform, the VR users reported higher enjoyment but revealed lower levels of gained declarative knowledge (Parong & Mayer, 2018; Maransky, Terkildsen, & Mayer, 2019). This suggests that the heavier cognitive load inherent to VR - or, perhaps, immersive media in general - prevents users from processing incoming facts into long-term memory.

This leaves us with two lingering questions: *What type of learning is best supported by VR?* and *How do we effectively engage learners in immersive VR without overwhelming them?* The former question will be addressed in Chapters Three and Four, while the latter is informed by methods for offloading cognition that can offset the risk of cognitive overload.

I have mentioned Weisberg and Newcome's (2017) argument that gesture can offload cognition. Mayer & Moreno (2003) cite three other relevant methods of reducing cognitive load in VR: *segmenting information*, *offloading cognition*, and *pre-training*.

[23] The theoretical correlation between interest and higher learning outcomes is sometimes known as "interest theory" and is alluded to in some of Mayer's research (see Parong & Mayer (2018) as an example).
[24] Consider the difference between "the flower undergoes photosynthesis" and "this is how flowers photosynthesize sunlight to make ATP."

Segmenting information breaks content into separate smaller pieces, which users can complete at their own pace (Mayer et al. 2019). Segmenting reduces cognitive demand by decreasing the amount of content presented. *Offloading cognition*, previously defined by Weisberg & Newcombe (2017), can free up mental capacity by storing extraneous information into actions or tools. A signpost on a highway is a real-world example of offloading cognition; instead of being forced to memorize highway numbers, a driver can simply recall their location by glancing at the words on a passing sign. *Pre-training*, teaching factual content before completing a related immersive experience, can be very useful. In their case study, Meyer, Omdahl, & Makransky (2019) split up participants into four groups of varying conditions: immersive VR users doing pre-training, immersive VR users not doing pre-training, 2D video users doing pre-training, and 2D users not doing pre-training. (I will focus only on the first two conditions.) The researchers noted that VR with pre-training resulted in much higher information transfer and retention than VR without pre-training. In other words, users were able to absorb and retain more information if they learned essential terms and other declarative knowledge *before* stepping into VR. This study has significant implications for how VR might be integrated into a classroom curriculum, which will be discussed further in Chapter Four.

Summary

As detailed in this chapter, VR is best used when its design integrates the affordances of presence, immersion, embodiment, and interactivity. VR can enable learning through strategies like experiential, situated, and embodied learning. However, VR can also impede learning because the technology lends itself to high cognitive load, paradoxically due to its best affordances.

On one hand, there are unique affordances built into virtual reality that can and should be utilized to their best ability. On the other hand, VR learning designers must be careful not to overwhelm prospective users with rich information. How do we address the limitations of VR for learning while taking advantage of its strongest affordances? It is a tenuous balance to maintain, and one that is difficult to create without thoughtful long-term iterative design.

Chapter Three will analyze the theories discussed in this chapter through the lens of the CLEVR Project, a VR-based game for cell biology learning that I have been a part of since the summer of 2017. It also discusses the unexpected obstacles and solutions that we came up with over the course of the project; indeed, CLEVR was as much a learning experience for the design team as it was for our prospective users.

Chapter Three: CLEVR Case Study

The previous chapter introduced a deluge of pedagogical jargon about the affordances and limitations of virtual reality in learning. I will now pivot from general overviews of learning frameworks to an in-depth discussion of CLEVR (Collaborative Learning Environments in Virtual Reality), an immersive VR experience that has been in development since mid-2017. I particularly wish to discuss the iterative design of this project through three major processes: how user tests and user feedback influenced subsequent iterations of the game; how certain design decisions within the game were intended to offload cognition or maximize use of other learning affordances; and how we continuously adjusted our user testing methodology as we gained a more insightful understanding of what users were learning from CLEVR. To put this more succinctly, I will analyze the *methodology*, the *design*, and the *iteration* of CLEVR with a focus on the project trajectory from Fall 2019 to Spring 2020. I will also differentiate between CLEVR (the name of the overarching project) and *Cellverse* (the name of the immersive VR experience that emerged from CLEVR).

Many case studies in educational VR are limited in scope; many researchers use third-party software in their research that they had no role in designing, and others are only peripherally involved in the development of the experiences they test. Most of all, most research books, papers, and articles only discuss the successful end results of VR development endeavors. It is as if the previous design cycles of scrapped decisions, technological frustrations, and inevitable failures are swept under the glossy sheen of a playable final project. I believe there is much value to be found in the long and winding journey of pedagogical design, and that learning from failure is more relevant to a relatively new field like VR than most. This chapter attempts to encapsulate the successes, failures, and results-in-between that emerged from both developing and researching CLEVR. Ultimately, Chapter Four will link these findings to a more thoughtful understanding of designing and integrating VR in educational spaces.

The Story of CLEVR

CLEVR is an ongoing research collaboration between the MIT Education Arcade and the MIT Game Lab. It is funded by Oculus Education and has been developed by an interdisciplinary team of researchers, game designers, programmers, and artists, with no small contribution from numerous students, teachers, scientists, and other subject matter experts. I have been working on CLEVR since June 2017, at its beginning stages of development. I cannot grant myself a specific title, as my own contribution to the project has evolved over the last few years. In no particular order, I have served as a writer, researcher, user testing lead, narrative developer, character designer, 3D modeler, concept artist, and storyboarder.

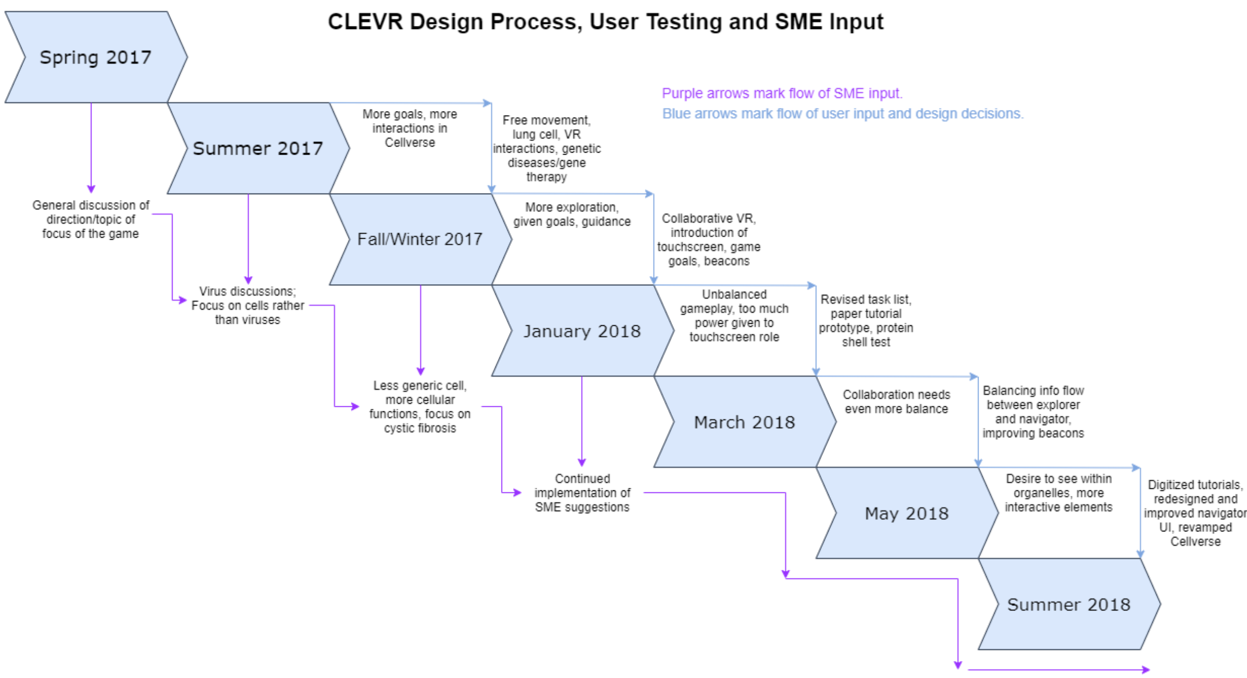
Cellverse, the game produced through the CLEVR Projects, has been developed as both a single and two-player game that expands upon concepts of cell biology, particularly cell organelles and cell processes. Our team used the Next Generation Science Standards (NGSS, 2013) as a baseline for *Cellverse*'s educational content, which is best suited for high school and undergraduate-age student users. The software was built using Unity 3D and is supported by the Oculus Rift system. At the time of writing, the narrative of CLEVR *Cellverse* is as follows: the player is a student intern using a remote-controlled microbot to navigate through a human lung cell. The cell, much like its human host, is stricken with an unknown form of cystic fibrosis. The player is tasked with exploring the cell's internal structure and observing the cellular process of transcription and translation to figure out which form of cystic fibrosis is affecting the cell, in order to provide the unnamed patient with the most effective care.[25] To accomplish their task, the player is equipped with a number of tools and informational tips that allow them to shift between different levels of scale, read descriptions of selected organelles, and perform other functions.

As was noted, this chapter primarily expands upon research and development completed between Fall (September) of 2019 and Spring (May) of 2020. For full disclosure, I have previously published a paper detailing CLEVR's design process from May of 2017 to roughly August of 2018 (Wang et al. 2019). To focus on the most current findings and avoid redundancy, I will keep my discussion of CLEVR's early design and development relatively concise.

Chapter 3 covers both design decisions and user testing procedure over the course of the last few years; Chapter 4 will critically reflect on these data and use what we learned from CLEVR to develop guidelines and suggestions for creating VR for learning. One of the glaring weaknesses in current VR research is a lack of documentation for such projects; most researchers have either used 3rd-party software for user testing or otherwise have

[25] For those who require a reminder of biology jargon: transcription is the process by which DNA is copied into RNA, and translation is the process of RNA being copied into proteins that perform various essential functions in the body. Transcription and translation make up the Central Dogma of molecular biology.

served non-developmental roles in their VR experience's creation process. I believe it is important for people who write about educational VR to have firsthand experience in creating said VR. In such a nascent field of study, it is also vital to publish both the successes and failures of ongoing design to evaluate internal performance and to inform future audiences. Failure, after all, is an important aspect of users learning to master gameplay. If a well-designed game enables failure as part of learning to succeed (Gee, 2014), game development should reflect a similar philosophy.



(Figure 7: Iterative CLEVR design between Spring 2017 and Summer 2018 based on user and subject matter expert (SME) feedback.)

May 2017 - August 2018

The early stages of CLEVR were perhaps the most dramatic in terms of game design and development. We began by exploring virology as a potential topic but decided to focus on cell biology and genetic diseases instead. From there, we began to experiment with different formats of depicting animal cells within VR environments. While we considered ways of manipulating a cell from an "outside-in" point of view, we eventually settled on an "internal" view of a cell, allowing a potential player to navigate within an enclosed environment (Figure 8).

Figure 8: Screenshot of player navigating through cell in a Summer 2017 version of *Cellverse.* This point-and-move method became known to the development team as "Spider-Man"-style navigation.

An overarching goal of this project has been to create an "authentic" or realistic depiction of the cell. This is reflected in our attempts to model realistic 3-dimensional cellular structures as well as in the relative size and density of the cellular environment. Contrary to many simplistic cellular models common in biology textbooks, cells are dense and packed with an incredible variety of structures (Figure 9). The sense of density, of needing to navigate through hundreds of ribosomes, mitochondria, and other organelles, was a feeling that we wished to convey within the game.

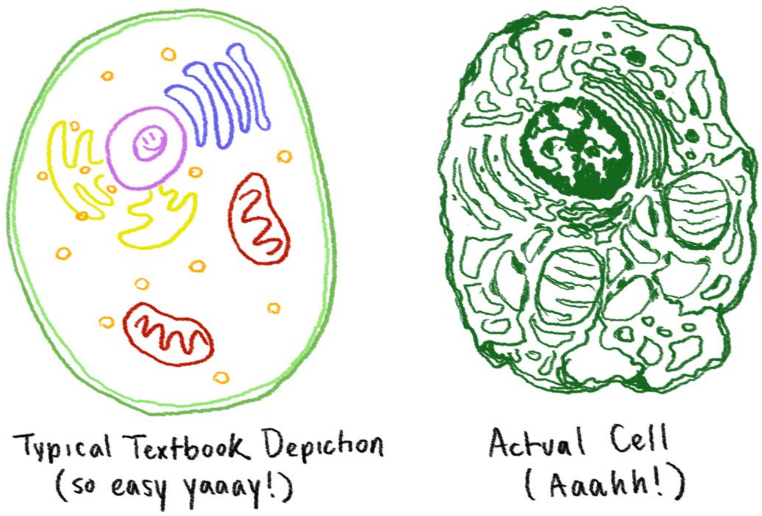


Figure 9: Author's drawing comparing a simplified textbook depiction of a eukaryotic ("animal") cell to a photographic scan of the real cell.

CLEVR's development has relied on an iterative design strategy (Figure 7). We created the game over the course of several design cycles, each lasting between 1-3 months. During and after each period, we invited user testers to play the game and provide feedback. Analyzing and incorporating user feedback enabled us to continuously improve the game experience. Between 2017-2018, we invited a variety of testers, most of whom can be classified into one of two groups: biology subject matter experts (SMEs, encompassing researchers, scientists, and professors of varying disciplines) and prospective users (students, teachers, and other non-SMEs). Top-down (SME) and bottom-up (user) feedback was instrumental in shaping the visual design and gameplay mechanics of *Cellverse* (Wang et al., 2019). Top-down feedback from SMEs enabled us to design an authentic representation of the cell; bottom-up feedback from other users, particularly teachers and students, enabled us to reveal the potential learning affordances embedded within the game.

During the summer and fall of 2018, our goal was to create a two-person version of *Cellverse* that used two major “viewpoints”: an in-VR view of the internal cell, and an “outside” view of the same cellular environment hosted on a touchscreen tablet interface (Figure 10). At this stage, developing *Cellverse* as a cross-platform game served two major purposes: one, to test the potentialities of a collaborative VR game for learning, and two, to offload the potential cost of purchasing VR equipment should *Cellverse* eventually make its way into classrooms. It also served to offload cognition on the part of each player because the partners are equipped with different tools specialized to their perspective. The in-VR player (the “explorer”) is able to experience an in-depth internal view of cell organelles and functions, while the out-VR (the “navigator”) has a birds-eye view of the cell and is in charge of the game’s “tasklist.” In this manner, each player oversees their own unique responsibilities but is limited in what information they possess without the aid of their partner. This creates a “positive interdependence” that involves both players in the problem-solving process (Thompson et al, 2018).

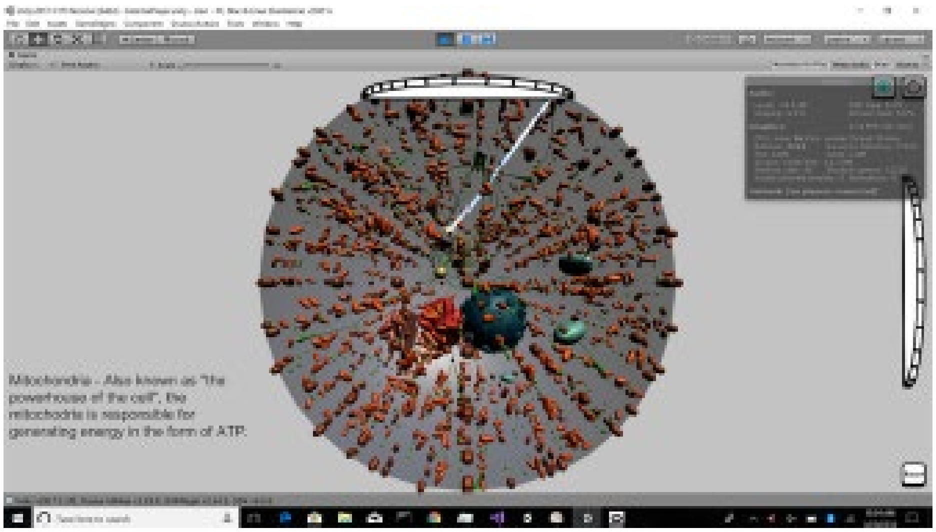


Fig: 10: Screenshot of early tablet view (Navigator) prototype, circa winter/early spring 2018.

Each phase of the design process focused on a different aspect of CLEVR's design and development. Because of this, it is useful to note the research questions or hypotheses we had in mind during certain time periods. The conjectures listed below reflected our interest in testing three major aspects of *Cellverse* between 2017-2018: authentic design, embodied learning, and collaboration. We had three hypotheses:

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.[26]

[26] Wang et al, 2019.

Evidence addressing these hypotheses is presented in detail in Wang et al. (2019). As we continued to develop *Cellverse*, we learned more about the affordances and limitations of VR. In turn, our research questions and hypotheses also evolved.

Summer 2019

The period of Fall 2018 - Spring 2019 was a relative lull in both development and user testing. Instead, the project team focused on research for the collaborative game. In Summer of 2019, the team turned to implementing what we had learned into the game. Due to extraneous circumstances, I was not present during this development phase.

First, *Cellverse* shifted from a cross-platform collaborative game to a single-player game contained entirely within VR. Because there was no longer a partner available to supplement tasks or goals, this required a drastic overhaul of the in-game environment as well as additional tools. Major changes can be summarized as follows:

1. The "navigator" (tablet-using player) had access to a task list that provided guidance. In the new single-player version, guidance was mediated through the creation of an NPC (non-player character) called FR3ND, a minibot who assists the player throughout the early half of the experience.
2. The cellular environment was completely overhauled to depict the interior of an ionocyte, a critical component of understanding cystic fibrosis. Cellular organelles and other structures were similarly remodeled. This set us back a number of months in game development.

3. The development team introduced the ability to shift from "microscale" to "nanoscale," enabling the player to view structures and processes that would normally be impossible to see at the cellular scale.
4. Players could now begin the game with a seamless tutorial that taught them VR gameplay controls (movement, selection, et cetera). While we had an in-VR tutorial before Summer 2019, it was not seamless and required someone to manually transition between software files. The design shifted from being separate from the game to being well-embedded in the game.

Pre-Fall 2019: CLEVR Design Decisions

Relative to the most recent user testing cycles, 2017 - Summer 2019 did not prioritize testing learning outcomes. In other words, we did not focus on comparing learning outcomes of *Cellverse* users versus other, non-VR experiences teaching the same subject. The questions that we asked of users primarily centered around engagement with the experience and comfort with the Oculus Rift technology.[27] Naturally, most of the data that we collected during this phase was qualitative in nature. We paid particular attention to the topic of *offloading cognition*. One consistent line of feedback from our user testers was that the initial introduction to the game – that is, dropping the player straight into the cellular environment without preamble – was initially confusing or disconcerting (Figure 11). As we intended to keep the *Cellverse* environment as scientifically realistic as possible, we had to think of ways to make the game less overwhelming without sacrificing too much

[27] To see the feedback form that we used during Spring-Summer 2018, please see Appendix 1.

realism. The tools and functions that we developed in subsequent game iterations, which are listed below, were developed to smooth transition into *Cellverse* and allowed for players to focus on gaining intended learning outcomes without being forced to simultaneously remember basic cell biology concepts.

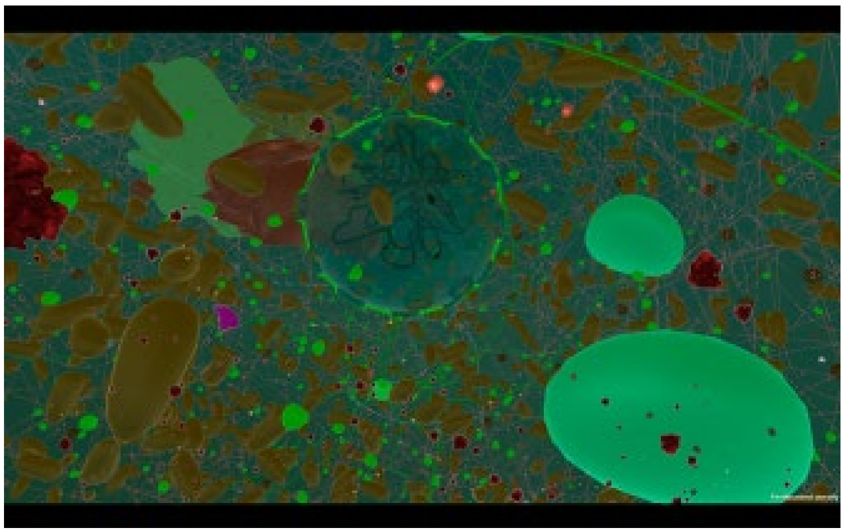


Figure 11: Screenshot of VR view prototype, circa winter 2018. This depicts the sheer density of *Cellverse* during this period, reflecting realistic densities of cellular organelles.

Tutorial

As previously discussed, the Summer 2019 development team created a tutorial that teaches essential game controls and transitions directly into the "main" game. The ionocyte cell we used as a model for *Cellverse* is shaped roughly like a two-legged octopus. The design team decided to have players start gameplay within one of its leglike "projections," which is less densely packed with organelles and structures than the cell's "body." This is advantageous in many ways; the player is less overwhelmed when they first begin the experience, and they can focus on learning essential gameplay instructions without being distracted by the surrounding environment. This enabled the tutorial to be embedded more seamlessly into the game.

The tutorial, led by the friendly microbot NPC "FR3ND," teaches the player how to turn and look around, move within the virtual environment, and uses in-game tools like the clipboard and dashboard (Figure 12). While teaching users how to head track (look around) may seem extraneous, we have noticed that our user testers have either never used high-fidelity VR before or only used it briefly. Due to the immersive nature of *Cellverse,* we wanted users to be aware that their physical bodily movements in the real world could change their viewpoints in the virtual world. As the user progresses through the tutorial at their own pace, they can make their way towards the main body of the cell where the bulk of gameplay occurs.

Figure 12: A screenshot of the tutorial area, where the player begins the game. Note the simple and empty background devoid of extraneous content.

In-Game Guidance

Guidance provided by FR3ND was not limited to the tutorial. After the tutorial, FR3ND gives hints as to the player's next goal, "finding the organelle with translating, bound, ribosomes," and provides more clues should the player not find the correct organelle within a certain time. To monitor their progress, players are given an in-game menu or "dashboard" that replaces the collaborative version's tasklist. The dashboard contains a checklist that records the evidence they collect over the course of the game. It also provides the means for the player to diagnose the cell's condition using the evidence they collect (Figure 13).

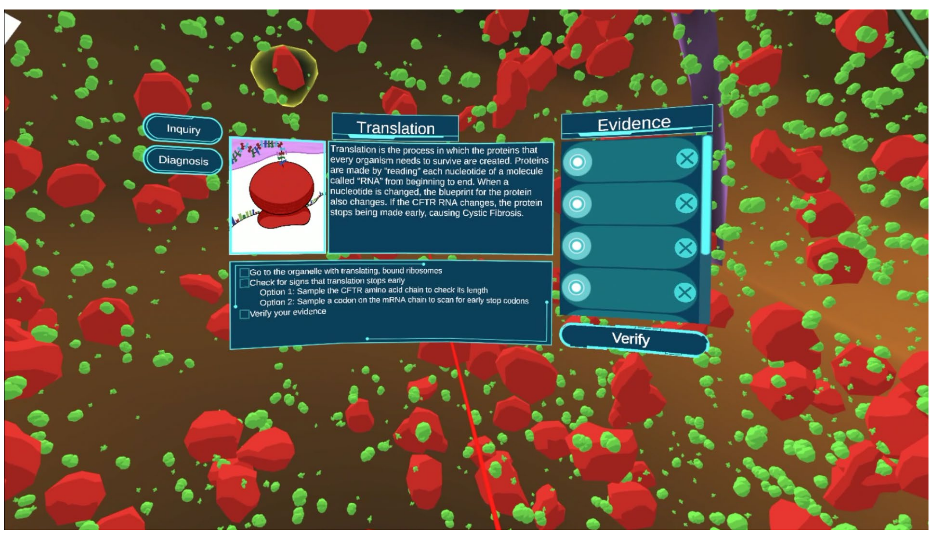


Figure 13: Player dashboard, showing the checklist of tasks and an empty evidence list.

Clipboard

Players begin the game with a virtual "clipboard" that appears on their left hand when toggled. This tool serves two major functions. First, it allows players to view descriptions of selected organelles. Many objects within the game are selectable; when clicked on, a summary of the structure's purpose and function displays on the clipboard (Figure 14). Second, it allows for players to record pieces of evidence using the "sampling" function (Figure 15). Sampling objects inside the cell allows players to gather potential clues about cellular function to solve the problem of what is wrong with the cell. Players verify and then use the evidence to diagnose the type of cystic fibrosis in the cell by reviewing different forms of cystic fibrosis to make an educated diagnosis.

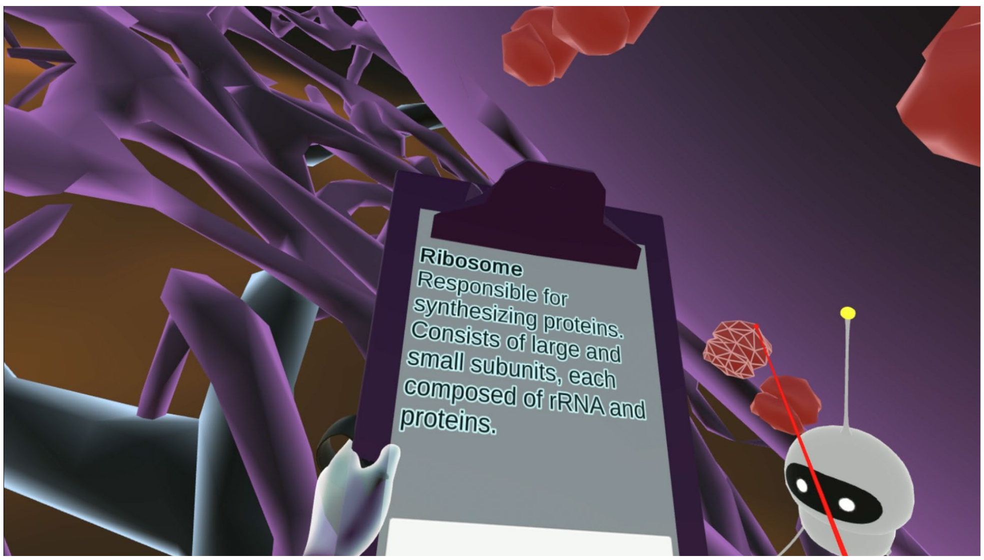


Figure 14: A screenshot of a user selecting a ribosome, with the corresponding description appearing on the clipboard tool.

Figure 15: Having selected an object, the player can "sample" it to record any interesting or unusual observations.

Fall and Winter 2019

Our Fall and Winter (roughly September to January) 2019 study drew from a user base of high school-aged students in the Somerville and Lawrence, MA area (n=113). These students ranged from 14-19 years of age and had taken or were in the process of taking AP and on-level biology classes. By tapping into the school-age populations of these two cities, we were able to draw from a user base of diverse ethnic and socioeconomic backgrounds.

The research questions that shaped this phase are as follows:

1. How does playing a VR-based game influence players' conception of cells?
2. How does experience in VR impact student learning?
3. How do students respond to using VR as a medium for learning?

While we still valued player comfort with and enjoyment of VR, we also were keen to understand *what* students were truly gaining from *Cellverse*. To quantify the learning outcomes, we prepared an assessment and a drawing task to test users' factual knowledge and conceptual understanding of cells.

We built the assessment on the online site Qualtrics for ease of data collection. The pretest assessment consisted of three major sections: a short-answer section asking for user VR and gaming experience; a cell biology section consisting of multiple-choice and ordering questions that gauged factual knowledge of cell biology, central dogma, and translation; and an interest section that gauged user interest in science and collected general demographic data. Users completed the assessment before and after undergoing the VR experience.[28] The posttest had an identical biology section and also included a spatial section where users could evaluate their own mental workload, adapted from the NASA Task Load Index (TLX) method.[29] We used this section to gain a sense of users' personal comfort, frustration, and/or confidence with playing *Cellverse.*

In the cell drawing task, we requested users to draw and label an animal cell from memory, then explain their reasoning in writing. This allowed users to visualize their mental models and their development over time. Once again, users did this task before and after playing *Cellverse.* In the posttest, users were also asked about how their conceptions of cells changed after playing *Cellverse.*

User Testing Methodology

Every user went through the following procedure:

1. Pretest assessment

28 See Appendix 2 for Fall 2019 Pretest questions and Appendix 3 for Fall 2019 Posttest questions.

[29] To see the original NASA TLX questionnaire, please visit https://humansystems.arc.nasa.gov/groups/TLX/downloads/TLXScale.pdf.

2. Pretest cell drawing
3. VR gameplay
4. Posttest assessment
5. Posttest cell drawing
6. Oral interview, which was used to gain initial feedback and gauge users' personal thoughts about their experience.

Findings from Fall and Winter 2019

The findings from Somerville and Lawrence provided a wealth of diverse feedback from the student users. I will elaborate on some of our findings below, drawing statistical data from a paper that is currently being considered for publication (Thompson et al. 2019, in press).

Cell Drawings

Many of the pretest drawings students produced were clearly derived from textbook images of animal cells (Figure 16, left). Nearly all drawings contained a spherical cell with an equally spherical nucleus. The mitochondria, or "the powerhouse of the cell," was another common addition. User 105, for example, produced a simplistic figure in their pretest drawing and, when prompted for the reasoning behind their drawing, simply remarked that they hadn't "drawn a cell in almost two years." Indeed, most of these students noted that they were reproducing these images from memories of biology courses.

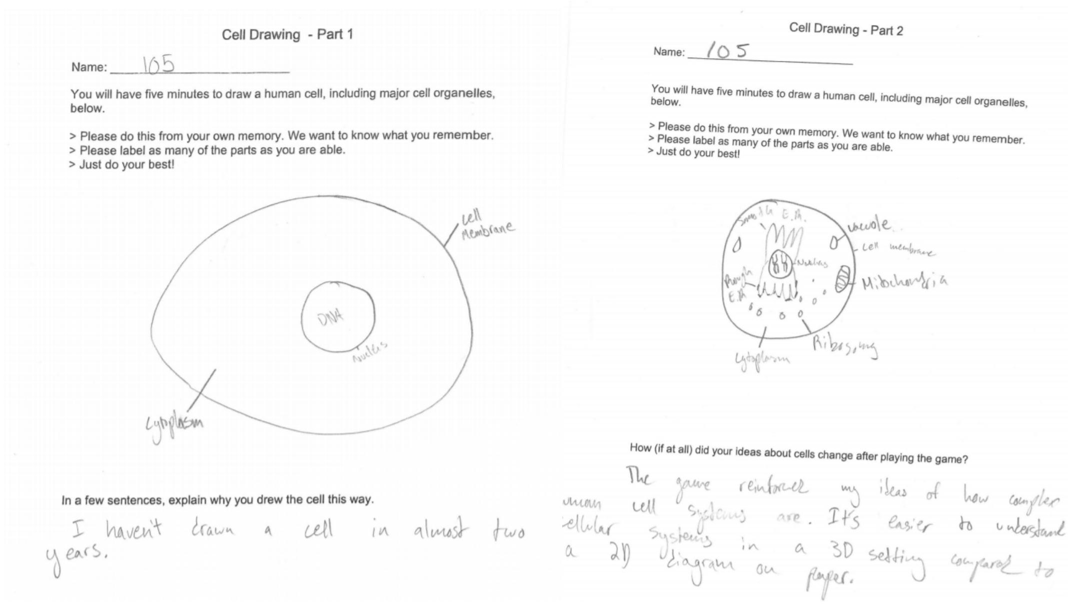


Figure 16: Sample cell drawing scans from User 105, pretest (left) and posttest.

After playing *Cellverse*, User 105 (above) had labeled 4 organelles or structures in the pretest; in the posttest, this number went up to 9. When asked about how their ideas of cells changed, they wrote down that *Cellverse* “reinforced my ideas of [sic] how complex human cell systems are. It’s easier to understand cellular systems in a 3D setting compared to a 2D diagram on paper.”

This phenomenon was not limited to a few individuals. (Figure 17). Figure 18 shows that users overall were able to identify and label far more organelles in their posttest drawings. (A few structures, like the cytoplasm or cell membrane, showed a significant decrease. This may have been because these structures were not labeled within the game.) Students’ drawings became richer and more complex when they experienced the density of the cell.

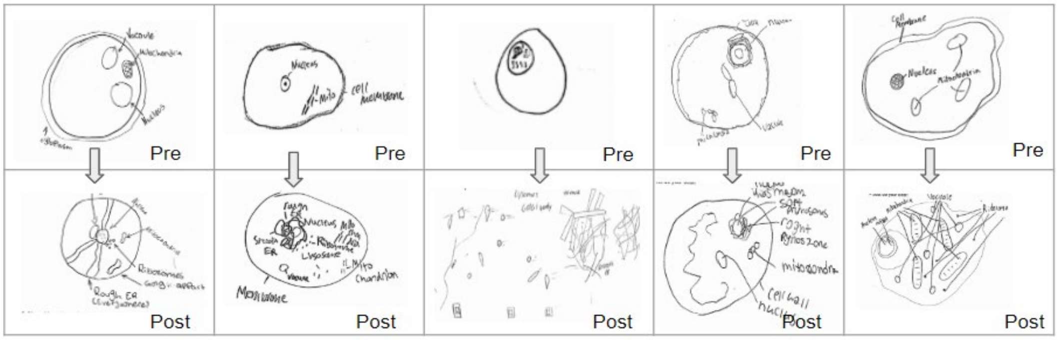


Figure 17: Sample cell drawings from student users (Thompson et al. 2019, in press).

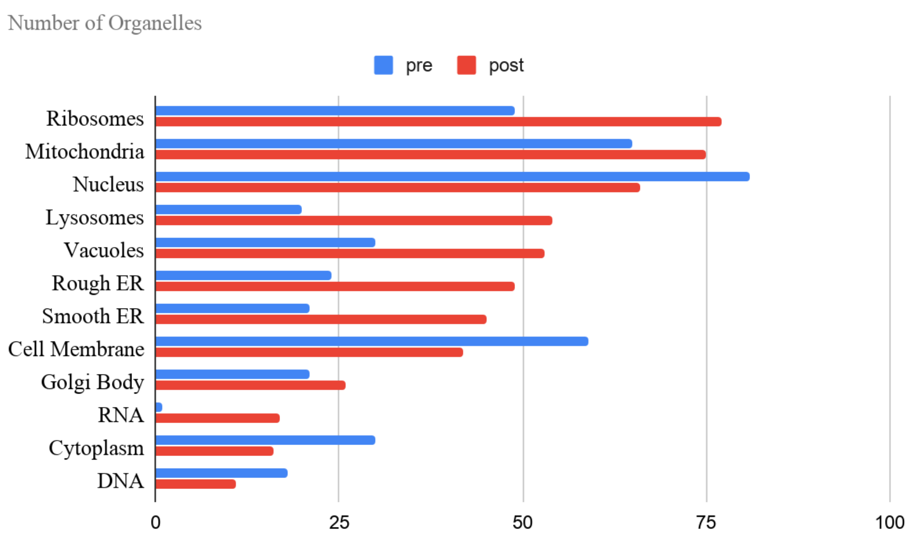


Figure 18: Graph conveying the overall number of organelles students drew before and after playing *Cellverse* (Thompson et al. 2019, in press).

User Feedback

After recording and transcribing student interviews, we scoured their feedback for patterns of common keywords (Figure 19). Responses suggested that there were aspects of *Cellverse* that a significant number of users appreciated, namely its sense of presence (n=47), its immersive/realistic nature (n=38), and its ability to convey visual information (n=39). Mentions of the cell being "dense," "crowded," or "packed" were common:

> Interviewer: What do you think you have learned about cells through this experience?
>
> Student 1: Well, I definitely appreciate how densely packed cells are with stuff, and every time I've seen a drawing of it, it's like, half-empty. Like, just a couple of organelles thrown in, but I realize now there's a lot of stuff in there. And especially the smooth ER and rough ER and stuff were, like, much denser than I would've expected it to be.

Students who described themselves as "visual" or "hands-on" learners made mention of this when explaining their enjoyment of the experience:

> Interviewer: How does [*Cellverse*] compare to other ways you have learned about cells?
>
> Student 2: It's much cooler. I'm a visual learner so it was way easier for me to learn that way.

Students also commented critically on the learning curve of the game, finding navigation and orientation within the VR space to initially be difficult or unintuitive (n=29):

> Interviewer: How did it feel to move around or navigate [in *Cellverse*]?
>
> Student 3: It felt - weird, cause, like, you were floating in a cell. The movement was, like, a little weird because you had to point everywhere.

Some users, particularly those familiar with VR or console-based video games, offered suggestions for improvement:

Interviewer: How did it feel to move around or navigate [in *Cellverse*]?

Student 4: It was good. At first it was a little weird, how you'd press the button to move and you'd only go in one direction and if you moved your remote, you wouldn't change directions. That might be cool, make some nice curving arcs.

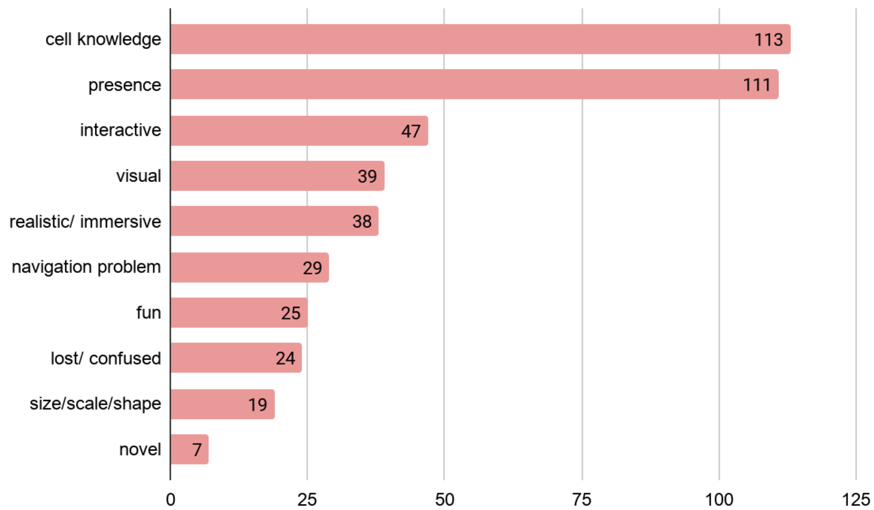


Figure 19: Graph showing keyword frequencies in user interviews (Thompson et al. 2019, in press).

User Assessment

Although the cell drawings and user interviewers pointed to high user engagement in *Cellverse*, we were startled to see that learning gains were not reflected in the posttest assessment data. There was a sizable gap between students' self-conception of their learning and their actual outcomes. We found no significant difference in factual cell and organelle knowledge when we compared the pre- and post-assessment scores (Thompson et al. 2019, in press). We had initially hypothesized that VR would be productive in teaching users about relative size and scale of cellular structures and added many size and scale-themed questions to test this. However, student scores relating to size and scale *decreased* from pretest (M=.50, SD=.12) to posttest (M=.28, SD=.12). Simply put, students were not learning about size and scale in *Cellverse*, and the nature of the experience may have left them even more confused about the topic.

These results suggested to us that we needed to rethink our user testing methodology, as the questions we had asked did not seem to correspond well to user learning outcomes. Our question evolved from “Is VR good for learning?” to “What types of learning is VR well suited *for*?”

Spring 2020

Changes to Testing Methodology

Despite the promising cell drawings and reports of high interest and motivation from our users, the assessments from Fall and Winter 2019 show that users were not gaining the factual knowledge that we had initially expected. Meyer, Omdahl, & Makransky (2019) have warned that users gain relatively low declarative (factual) knowledge using VR compared to other formats. Considering this and our experiences in the fall of 2019, we adjusted our user assessment and cell drawing task accordingly.[30]

First, we overhauled the user assessment from factual inquiries to process-based inquiries. Instead of asking if users knew the concrete term for the end result of translation, for example, they would be asked if they could outline the process of translation instead. (The nanoscale view of *Cellverse* allowed users to experience the process in action.) The cell drawing task was tweaked accordingly – participants were asked to draw the cell *based on what they learned in the game,* and users were asked to outline the process of translation. Next, given that users were not learning about size and scale from VR, we replaced many of those questions with spatial learning-based questions. We theorized that users obtained strong wayfinding skills by navigating throughout the virtual environment. Before and immediately after playing, users were asked to complete a series of timed performance tasks in which they found and located specific structures within *Cellverse*. Afterwards, we compared the times for their pre- and post-game spatial learning tasks.

[30] See Appendix 4 for the Spring 2020 data entry form.

To quantify learning outcomes, we needed to contrast the VR-based *Cellverse* game with a non-VR viewpoint. We devised that the head-mounted display provided an immersive 360-degree (stereoscopic) view that aided in the spatial and process knowledge learning experience. To test this theory, the development team created a non-stereoscopic version of *Cellverse* that can be played on a flatscreen computer monitor. While a user playing the non-stereoscopic game does not use an HMD, the rest of the experience remains identical.

In lieu of the changes listed above, our hypotheses for this phase were as follows:

1. A stereoscopic, HMD view will be more effective in helping students understand the complex environment of the cell than a non-stereoscopic, non-HMD view.
2. A non-HMD view will have a better impact on students' factual knowledge than a stereoscopic view.
3. Biology knowledge and gaming and VR experience will have an impact on students' gameplay.

Our Spring 2020 user testing population shifted from local high schools to the MIT community, who were recruited through advertising and word-of-mouth. This was advantageous in many ways: it was more convenient to recruit potential testers and randomly sort them into one of two testing groups (discussed below). Drawing from the MIT community also provided us with users with a diverse range of academic backgrounds. By extension, our testers had a wide range of biology experience. Users consisted primarily of MIT undergraduate students, some graduate students, and a small number of staff (n=62). Half of the users played the VR version of *Cellverse* with the HMD, while the other half played the non-stereoscopic monitor-based version. Finally, users were sent a post-survey a week after their respective testing sessions that ascertained what they could remember from playing *Cellverse*.

Findings from Spring 2020

Our goal was to test 100 users during the spring semester, but extraneous circumstances forced us to prematurely conclude in-person testing. We are currently analyzing user data from the 62 users we successfully tested and have already noted some interesting observations that seem to partially correlate with our research hypotheses. At the time of writing, we do not have conclusive evidence comparing the learning outcomes of the stereoscopic HMD version of *Cellverse* with the non-stereoscopic version.

Within our randomized user group, biology experience among users ranged wildly, as did experience and comfort with VR and console-based video gaming (whose use of handheld controls is similar to the Oculus Rift). Users who had biology experience in recent years and/or were comfortable with console gaming seemed to have an initial Proficiency with language also mattered; users who knew less English were more likely to be disoriented by the in-game instructions.

Cell Drawings

In this iteration of the cell drawing tasks, we did not just look for labeled organelles but also relative positioning of organelles and structures within the cell. Due to the wide range of cell biology experience among our users, their drawings varied widely in detail and quality.

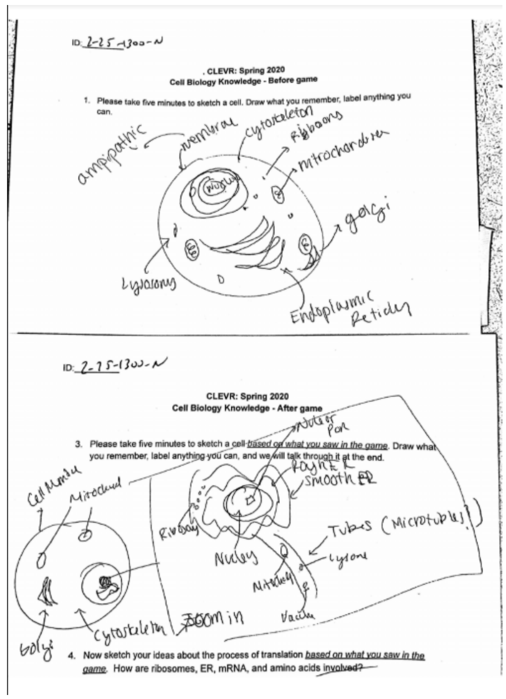


Figure 20: A pretest (top) and posttest cell drawing from a sample user. Note the labeled "tubes" in the posttest drawing, which the user mistook as an organelle.

A careful look at the cell drawings reveals some peculiar patterns among certain users that had not previously appeared during the Fall tests. For example, Fall users consistently drew their cells as round or ovular, both in the pre- and post-test. Some Spring users also drew round cells, but others drew square, elongated, or amoeba-like "blobby" shapes. A few users in both the Fall and Spring sessions drew "3D" models.

Misconceptions about cell structure were also more common in the Spring cell drawings. The user featured in Figure 20 played the non-stereoscopic (2D screen) version of *Cellverse* and redrew their cell drawing at two different levels of detail. In the more detailed view, the user correctly included several organelles, but also drew "tubes" that were neither labeled in the game nor were part of the cell. When asked, the user claimed that they "never knew that cells had tubes in them that were less crowded than the main part of the cell." This was a clear misconception on the user's part; they had mistaken the tubelike extensions of the ionocyte as a part of every animal cell. Several other users made the same claim in their cell drawings, which iterated to us the difference between "biology" and "non-biology" users (Figure 21). Due to their lack of a factual knowledge foundation, people who had not studied cell biology recently were more likely to come away with misconceptions inadvertently produced by playing *Cellverse*.

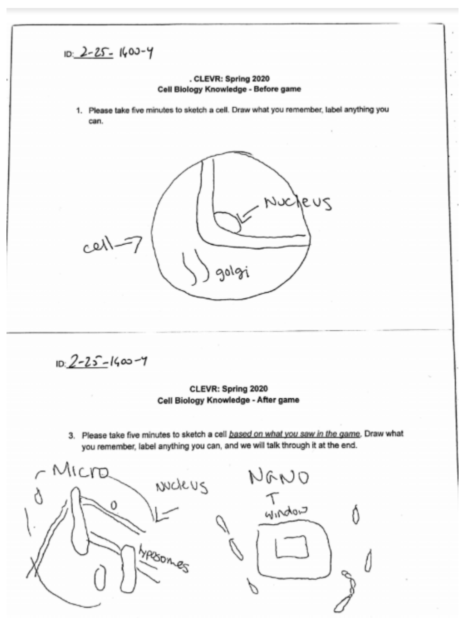


Figure 21: Another example of a user drawing "tubes" or "tunnels" within the cell. Note that the cell retains its round shape in the post-drawing.

The translation aspect of the cell drawings also produced interesting results when we amalgamated the data. Figure 22 below shows the frequency of organelles and structures that appeared in the translation cell drawings, both pre- and post-play of

Cellverse. Excepting DNA and proteins (the former having not appeared in *Cellverse*), all the listed structures were depicted with greater frequency in the post-drawings.

	includes DNA	includes RNA	includes mRNA	includes tRNA	includes ribosomes	includes amino acids	includes proteins	includes ER	includes translocation channels
pre	12	20	29	9	26	23	13	15	0
post	3	28	43	12	37	42	12	33	27

Figure 22: Table showing the frequency of organelles/structures depicted in the user translation drawing task, before and after playing *Cellverse.*

User Testing Observations

Although quantitative data analysis is still ongoing, we can clearly draw the following conclusions from the Spring 2020 data:

1. **Spatial learning and wayfinding knowledge gain is high.** Once well-acclimated to the virtual environment, users can recall and find specific objects far more quickly than when they first began the experience.
2. **Previous biology knowledge helps enrich user participation.** Users who stated that they had a biology background or had taken a biology class within the last year were able to acclimate more quickly to *Cellverse* gameplay. People do seem to gain more if they have a biology background, but it also

seems that people retain different nuggets of information depending on their level of knowledge.

3. **Users are gaining some level of process knowledge, even without a substantial or recent cell biology background.** Note that I am also including users who may have gained incorrect or inaccurate knowledge by playing *Cellverse*. One user with little biology knowledge learned about translation through the game, but incorrectly assumed that proteins were chained together by ribosomes to create amino acids (in fact, the opposite is true). While there was an obvious dearth of factual knowledge on this user's part, we can still consider this a successful transfer of process knowledge in the sense that the user understood translation as a series of steps leading to a final result.

Chapter Four: Reviewing the Benefits and Drawbacks of VR for Learning

What has CLEVR's design and user testing process revealed about developing virtual reality for learning experiences? In this final chapter, I will reflect upon the data and observations from Chapter 3 and use them to generate general guidelines for creating educational VR and integrating it into K-12 classrooms.

CLEVR and VR-based Learning Affordances

How does the CLEVR project fit in with the learning affordances outlined in Chapter 2? How does it compare to earlier findings from education and cognitive science scholars? When we overlay the CLEVR project with the frameworks discussed from Chapter 2, several frameworks immediately stand out:

- *Domain knowledge.* Like other science-based topics, cell biology works well as a domain for VR-based learning. CLEVR fits in Bailenson's (2018) DICE framework as an "impossible" experience – it allows users to accomplish the otherwise unfeasible task of shrinking down to explore the interior of a cell. Similarly, the project meets many of Dalgarno & Lee's (2010) guidelines for virtual learning environments. Being able to navigate through the cellular environment and observe processes in action contributed to "enhanced spatial knowledge representation"[31] for our users.

[31] This was Affordance 1 in Dalgarno and Lee's guidelines. CLEVR also successfully met the guidelines for Affordances 2 through 4.

- *Experiential learning.* Users, simply put, "learn by doing"; even making mistakes are meant to encourage, not discourage learning. By interacting with virtual objects in an open environment that encourages exploration, users were able to construct their own experiences in the game (Jantijies et al. 2018).
- *Embodied learning.* The entire game addresses users as though they are present within the cell. Interaction with the environment is not limited to simple navigation; much of it is meaningful. The player can "bump" into organelles or structures and must navigate around them when necessary, rendering them perceivable as solid objects. In nanoscale, players can move through the translocation channel, seeing RNA and ribosomes on one side and the formation of amino acid chains on the other. This movement within the 3D space allows users to better conceptualize translation as an active, moving process.

Reflections on CLEVR

Here, I will highlight the major achievements and stumbling blocks that we faced while designing and testing *Cellverse*. These reflect the status of the game at the time of writing and may be amended or resolved in the future.

What We Did Well

- *Creating an engaging virtual environment.* The *Cellverse* environment is bright and colorful, filled with low-resolution organelle models that evoke a sense of playfulness. Some objects at nanoscale are even capable of moving at realistic speeds, allowing for players to witness processes like translation in action.

- *Scaffolding the in-game experience.* After realizing how first-time VR users could easily become overwhelmed by the cellular environment, we restructured *Cellverse* with a tutorial that allows them to gently ease into their virtual surroundings. Throughout the first quarter of the game, an NPC guided them through the game mechanics and offered gentle reminders when needed. The gradual transition, moving from an "empty" to a realistically "crowded" space, made initial gameplay less overwhelming and segmented the game into digestible parts (Parong & Mayer, 2018).
- *Facilitating game mechanics.* We used only a few game controls – movement, selection, clipboard, and dashboard toggling – within the game. This made *Cellverse*'s fundamental mechanics easier to learn for users of different gaming experience levels.
- *Offloading cognition for factual learning*. As suggested by Mayer & Moreno (2003), we offloaded factual information into in-game tools like the clipboard. Instead of users being required to memorize facts about cells and cell organelles, they were able to access information whenever they needed it with ease.
- *User testing methodology.* Using the cell drawing task, we were able to see how users' visual conceptions of cells shifted and quantify their learning. The wayfinding task we developed during Spring 2020 allowed us to measure changes in spatial learning.

- *Managing motion sickness*. For the last 3 years, we have only had one user tester stop playing due to motion sickness caused by VR.

What We Could Have Done Better

- *Managing cognitive load in the single-player game.* The original two-player, cross-platform experience allowed for each user to manage their own unique information, reducing cognitive load, and allowing for spatial understanding through multiple perspectives. This mental resource management became more difficult in the VR-exclusive game, where one player must manage everything without assistance. While we have made a great effort to organize the early gameplay experience (see above), the latter half of *Cellverse* may require further in-game scaffolding to facilitate information retention and thus reduce load.
- *Lack of integrated gestures.* Other than certain buttons mapped to the Oculus Rift hand controllers, we did not account for natural gestures that could be used by users in the game. Future iterations might include tools that harness gesture, thus increasing player immersion.
- *Game pacing.* This may have been an issue of "over-scaffolding" the game after the Summer 2019 updates, when the development team was unable to test their new changes due to time constraints. After finishing the tutorial, post-Summer 2019 user testers were immediately prompted by FR3ND to find a specific organelle (the rough endoplasmic reticulum or ER). Because the command was so direct, players often neglected to spend time exploring the rest of the cell because they were so

busy searching for the rough ER. CLEVR developers may need to augment NPC AI to allow for greater flexibility in exploration.

- *Lack of pre-training.* Many of the Spring 2020 user testers recalled little to no cell biology learning (or had not taken relevant courses for more than a few years), which increased the initial learning curve of *Cellverse* for them. To level the playing field between biology "novices" and "experts," we may consider developing a short curriculum that allows users to regain prior knowledge before stepping into the game.
- *Inconsistent teacher input through design iterations.* We have brought in several teachers during the iterative design process but were unable to do so consistently throughout 2017-2020. There were several design cycles, particularly during Summer 2019, when the development team was unable to find time to invite teacher users to test the game. Having teacher input allows designers a firsthand understanding of technology integration in schools as well as individual teacher suggestions and concerns that can be integrated into the VR experience.

Guidelines for Designing VR for Learning

Based on what we have learned through previous research and through CLEVR, what should future designers keep in mind when creating VR for learning? How should designers engage in the iterative design process, and how should they incorporate user feedback into design? Moreover, what should one keep in mind when testing VR experiences with users? I have developed a list of guidelines below that address these overarching questions and serve as important takeaways for the reader.

I should add a disclaimer here: these guidelines are meant to serve as a living document and may not be fully comprehensive. While participating in the CLEVR project has revealed much to me about the nature of VR, it will be necessary for other researchers to document future VR experiences in other topics and build upon these findings. Immersive media technologies are rarely one-size-fits-all; what is useful for one type of experience may not be useful for another.

- **When in the preliminary stages of design, choose a topic or curriculum that can be uniquely harnessed by VR's affordances.** VR remains an expensive technology to build and disseminate, so being fastidious is necessary. Bailenson's (2018) DICE framework is particularly useful to remember – focus on topics that would be too dangerous, impossible, counterproductive, or expensive to explore in the real world.
- **Design with the affordances of VR in mind.** VR is not meant to be a replacement for other, older technologies, but a method of portraying learning objectives in a novel manner. Recall the unique affordances of VR - immersion, presence, embodiment, and interactivity – and leverage them through the design process. Pair them with educational frameworks relevant to the topic at hand, like experiential learning, situated learning, or embodied learning.

- **Remove extraneous details if they are not necessary for learning.** The game mechanics should reinforce the learning objectives, not distract from them. Recall that VR can produce high cognitive load in users, particularly three types of cognitive load: intrinsic, generative, and extraneous (Paas et al., 2003). The objective is to maximize intrinsic and generative load while minimizing extraneous load.

  Learning-based VR should not be developed in the same manner as VR for entertainment – remember that the goal is for the user to retain learning outcomes. While flashy animation, humor, or realistic visuals can increase a user's sense of presence, they also can detract from the learning experience if those factors are not relevant to the learning at hand.

- **Scaffold the experience. Information should be portrayed clearly and concisely.** The more complex the in-game environment, the more scaffolding is necessary. As we have discovered when developing CLEVR, a tutorial is extraordinarily helpful for easing users into any given game. Johnson-Glenberg (2018) noted that guided instruction promotes better learning: "Students benefit from pedagogical supports that help them construct conceptual models, or knowledge structures (Megowan, 2007)."
- **Provide guidance for using VR, particularly for users new to the technology.** Immersive VR remains a new and novel technology, and users need time to get used to using the equipment. Allow time for users to get comfortable with using the head-mounted display and hand controllers.

Guidelines for Integrating VR into K-12 Classrooms and Curricula

- **Match VR topics with K-12 curriculum standards and integrate 21st-century skills.** Recall, however, that VR is not good for declarative or factual knowledge (Parong & Mayer, 2018; Maransky, Terkildsen, & Mayer, 2019). Skills and content should be integrated in a manner that allows users to learn through the experience of being in a context-rich, highly interactive environment.
- **Use VR in areas that align with the affordances of the technology.** As I have discussed in Chapter 2, VR is a poor medium for disseminating factual knowledge and should not be used to deliver fundamental information (Moreno & Mayer, 2002). Moreover, the technology should not be used to simply regurgitate factual knowledge. What students learn in VR can and should be different than what they learn in other media formats. Perhaps they can learn specific contexts within vivid environments (situated learning), learn using their entire body (embodied learning), or learn by practicing activities on their own instead of watching someone else demonstrate (experiential learning).
- **Promote essential and generative processing through strategic division of information.** Students with more content knowledge will gain more than those with less experience. Moreover, segmenting information by dividing the experience into levels, chapters, or self-contained environments helps to reduce cognitive load. Pre-training – providing students with factual

knowledge before playing – should occur whenever possible, as mastery of essential knowledge before using VR allows users to absorb and retain more information (Meyer, Omdahl, & Makransky, 2019).

- **When working alongside educators, they should always be "in the know."** It is enormously useful to work alongside teachers throughout the design process, including in the preliminary stages. Effective codesign supports educators in their developmental trajectory for learning VR (Thompson et al., 2020). This is also what makes iterative design advantageous – designers can bring in teachers or other users to evaluate the in-progress experience to ensure its worth. Teachers should be well informed of VR's unique benefits so that they know how best to handle the technology in their classrooms. Designers should also have a clear understanding of teachers' environmental constraints, whether it is due to finances, equipment, or organizing students, and address these issues promptly within VR development.

Final Reflections

VR is a technology that, while relatively expensive, is now within reach for many educational institutions. This thesis has reflected upon the design and development of VR software for K-12 classrooms that can tap into learning needs still unaddressed in traditional curricula. While VR offers many opportunities to address modern learning needs in novel ways, there are clear limitations to the technology – namely heavy cognitive load – that must be kept in mind. To create an experience that produces strong learning outcomes without becoming mentally overwhelming, VR creators must iterate on thoughtful designs with user input. And, to understand the unique forms of learning that come out of VR experiences (situated, experiential, and embodied learning), researchers must be able to assess VR-based learning outcomes in non-traditional ways.

Supporting the use of VR in K-12 learning through design requires the integration of research fields that do not regularly intersect – education, cognitive science, immersive technology, game design. By drawing from the matrices of recent research, this thesis has covered the successes and pitfalls of creating educational VR, and hopefully has offered an extended look into the iterative design process. Due to the nascency of pedagogical VR research and the ensuing lack of consistent research guidelines, CLEVR has been as much a learning process for us designers as it will be for our future student users.

Because VR remains a nascent field of academic research, I believe that this thesis has generated numerous branching questions for myself and future designers to consider. What are other methods of offloading cognition to increase learning that did not appear in CLEVR? What learning outcomes can students draw from VR? When performing user tests, what assessment methods might be useful for gauging learning outcomes? For quantifying them? We may also consider how this will affect VR use in K-12 schools. How might VR design change between STEM and non-STEM subjects? How can designers embed accessibility into VR for teachers and students of diverse backgrounds? Are there special considerations for developing VR for children of different age groups?

In many ways, this thesis has only scratched the surface of a research field with vast potential. As immersive technologies become more affordable and schools take an interest in integrating them into classrooms, we must be prepared to design for future forms of virtual reality – and, indeed, for the future of learning.

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Appendix 1

<u>User Testing Feedback Form (June 2018 Version)</u>

Pre-testing Questions (These questions were asked before the playtesting experience, 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.)

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,…)

Appendix 2

Cellverse Fall 2019 Sept 12 Pre Cell Conceptions

Start of Block: GAMING EXPERIENCE

Q109 **CELLVERSE SURVEY**
Please answer the following questions to the best of your ability.

Name Please type your name or ID number here

____

____

____

____

____

VR experience Have you ever used a virtual reality headset before?

- ○ Yes - many times (1)
- ○ Yes - only once or twice (2)
- ○ No (3)

Q22 Do you identify yourself as a game player? (meaning board games or video games, not emotional games) :)

- ◯ Definitely yes (1)
- ◯ Probably yes (2)
- ◯ Might or might not (3)
- ◯ Probably not (4)
- ◯ Definitely not (5)

Q34 If you want to learn something new in biology specifically, how would you learn it? Where would you find the information?

____

End of Block: GAMING EXPERIENCE

Start of Block: CELL BIOLOGY

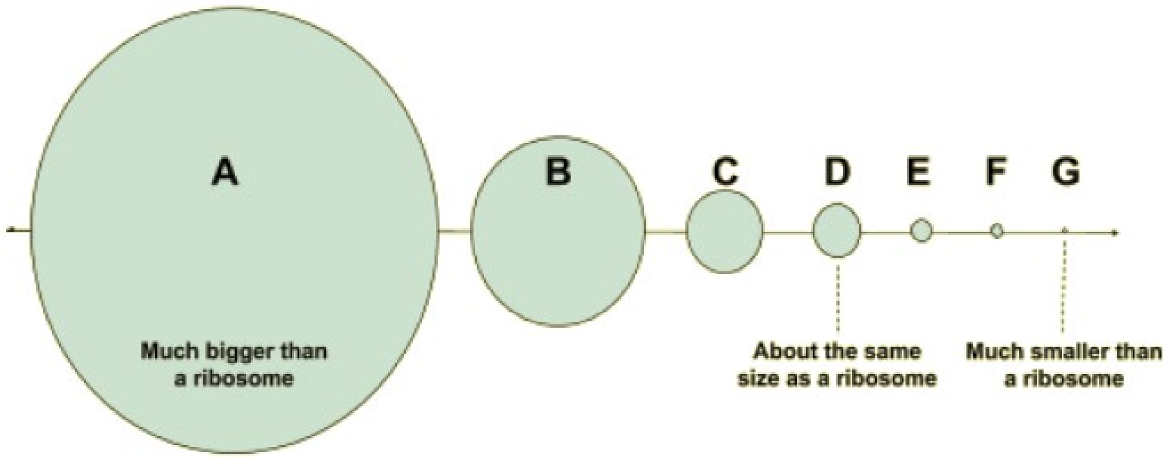
Page Break

Q24
PARTS OF A CELL Please answer the following questions to the best of your ability.

Q12 Here is a list of items that exist in a cell. Drag and drop to put them in order of 1 largest to 9 smallest. Put #1 at the top of the list.
______ mitochondria (1)
______ nucleus (2)
______ endoplasmic reticulum (3)
______ tRNA (4)
______ Golgi body (5)
______ water molecule (6)
______ ribosome (7)
______ atom (8)

Page Break

Size: Please answer the following questions to the best of your ability. Please don't look anything up - we want to know what you know right now.



Here is a diagram with general sizes of different items in a cell. "D" is about the size of a ribosome. Choose a circle (A-G) that's about the same size as the part of the cell in the list below (mRNA, Translocation channel....).

	same size as A (1)	same size as B (8)	same size as C (2)	same size as D (3)	same size as E (4)	same size as F (5)	same size as G (6)
Nucleus (1)							
mRNA (2)							
lysosomes (3)							
amino acids (4)							
Proteins (5)							
Ions (6)							

Number: Give your best guess of how many of each organelle below would exist in a human lung cell.

	1 of the organelle (1)	2-5 organelles (2)	6-50 organelles (3)	51-200 organelles (4)	over 200 of the organelles (5)
Nuclei (1)	○	○	○	○	○
Ribosomes (2)	○	○	○	○	○
Mitochondria (3)	○	○	○	○	○
Proteins (4)	○	○	○	○	○
Smooth ERs (5)	○	○	○	○	○
Vacuoles (6)	○	○	○	○	○
Centrioles (7)	○	○	○	○	○

Estimate: Now try to give a number estimate of how many ribosomes would exist in the cell. (Please estimate an actual number).

____

Page Break

Q15
CELL ORGANELLES: Please answer the following questions to the best of your ability. Please don't look anything up - we want to know what you know right now.

Q16 These organelles use RNA to string together amino acids and create proteins, which are essential for cell functions.

- ◯ Nucleus (1)
- ◯ Golgi body (2)
- ◯ Ribosome (3)
- ◯ Lysosome (4)

Q18 These organelles generate ATP, which fuels cellular activities.

- ◯ Nucleus (1)
- ◯ Mitochondria (2)
- ◯ Smooth ER (3)
- ◯ Lysosome (4)

Q19 These organelles keep the cell clean by breaking down cellular waste.

- ◯ Lysosome (1)
- ◯ Nucleus (2)
- ◯ Golgi body (3)
- ◯ Vacuole (4)

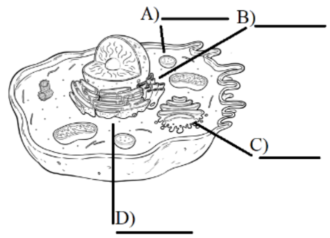
Q20 This organelle encloses the genetic information used by the cell to make proteins.

- Lysosome (1)
- Nucleus (2)
- Golgi body (3)
- Smooth ER (4)

Q41 This organelle forms a stable twisted structure that connects adjacent cells together.

- Golgi body (1)
- Nucleus (2)
- Intermediate filament (3)
- Endoplasmic reticulum (4)

Q43 Below is an image of a cell from a textbook. Based on the image below, which organelle packages and distributes proteins to the rest of the cell? Label the organelle of your answer.



○ Area A (1)

○ Area B (2)

○ Area C (3)

○ Area D (4)

Q45 The image of a cell in the question above is not entirely accurate. What suggestions would you make to make the cell more realistic?

____

Page Break

Q42 TRANSLATION: Please answer the following questions to the best of your ability. Please don't look anything up - we want to know what you know right now.

Q67 Below are the steps of creation of a protein called CFTR. Drag and drop the pictures to put the creation of the CFTR protein in the correct order.

______ DNA undergoes transcription (1)

______ CFTR protein reaches the membrane and becomes a channel (2)

______ CFTR protein is folded inside the ER (3)

______ mRNA encounters ribosome (4)

Q49 During translation, the ________ is sandwiched between the two halves of the ________. At that point, the ________sequences are decoded from nucleotides.

- a. DNA; tRNA; amino acid (1)
- b. mRNA; tRNA; amino acid (2)
- c. mRNA; ribosome; amino acid (3)
- d. DNA; ribosome; mRNA (4)

Q50 Where in the cell does the majority of translation occur?

- a. Nucleus (1)
- b. Mitochondria (2)
- c. Ribosome (3)
- d. Endoplasmic Reticulum (4)

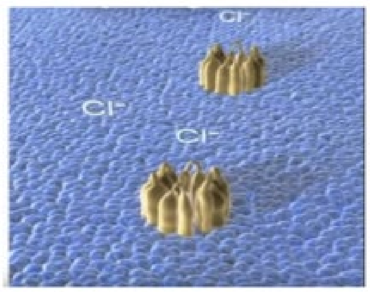
Q105 Which of the following could be signs that translation has stopped early? Check all that apply.

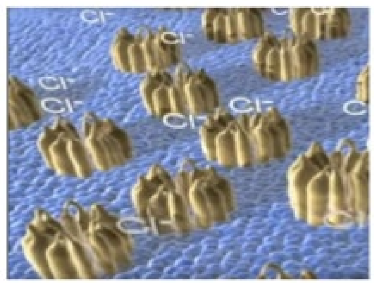
- ☐ The length of the amino acid chain. (1)
- ☐ An excess of translation enzyme in the cell. (3)
- ☐ A closed translocation channel. (4)
- ☐ An early stop codon. (5)
- ☐ The number of ribosomes in the cell. (6)

Page Break

Q52 Membrane: Please choose one answer for the following questions unless otherwise instructed.

Q53 The image to the left depicts a low density of CFTR channels, whereas the one to the right depicts a healthy density of proteins on the cell membrane. Why would a low density of channel proteins on the membrane be problematic?





- ◯ a. Low density of proteins yields no transfer of Cl ions (1)
- ◯ b. Low density of proteins yields little transfer of Cl ions due to its abnormal openings of channels (2)
- ◯ c. Low density of proteins means the viscosity of the lung's mucus is abnormal (3)
- ◯ d. Low density of proteins means the cell membrane is destroying protein channels (4)

Q56 You have detected 0 CFTR channel proteins on the cell membrane. What might have caused this issue?

- ◯ a. closed protein channels (1)
- ◯ b. inconsistent DNA transcription (2)
- ◯ c. misfolded proteins (3)
- ◯ d. slightly closed translocation channels (4)

Q57 Why is having enough protein channels on the membrane important?

- a. it allows enough transfer of sodium ions (1)
- b. it prevents mucus from being too thick and sticky to move out of the lungs (2)
- c. it allows enough transfer of chloride ions (3)
- d. both b and c (4)
- e. all of the above (5)

Q104 After the CFTR proteins are created, how do they get to the membrane?

- The CFTR proteins move through the centrioles. (1)
- The CFTR proteins are transporter by the lysosomes. (2)
- The CFTR proteins are transported by the vesicles. (3)
- The CFTR proteins are transported through the microtubules (4)

Page Break

End of Block: CELL BIOLOGY

Start of Block: INTEREST AND CONFIDENCE

Q31 Now, a few questions about you.

Q63 How confident are you that you can do the following:

	Not at all confident (1)	Not confident (2)	Neither confident nor unconfident (3)	Confident (4)	Completely confident (6)
Figure out the reasons why things happen in nature (1)	○	○	○	○	○
Use tables and graphs to figure things out. (2)	○	○	○	○	○
Figure out the relationships between organisms and environments. (3)	○	○	○	○	○
Look at data that I collect and see how it fits together. (4)	○	○	○	○	○
Connect the things that I am learning about in science with what I already know. (5)	○	○	○	○	○
Please select "not at all confident" here (7)	○	○	○	○	○

Q65 Share the following with us

	Strongly disagree (1)	Disagree (2)	Neither agree nor disagree (3)	Agree (4)	Strongly agree (5)
I find science enjoyable (1)	○	○	○	○	○
Science is just not interesting to me (2)	○	○	○	○	○
I like doing work in my science class (3)	○	○	○	○	○
I like learning new things in science (4)	○	○	○	○	○
In general, I find working on science assignments to be interesting (5)	○	○	○	○	○

Q64 How confident are you that you can ...

	Not at all confident (1)	Not confident (2)	Neither confident nor unconfident (7)	Confident (8)	Completely confident (9)
Do the kinds of things that scientists do. (1)	○	○	○	○	○
Solve the kinds of complicated problems that scientists have to solve. (2)	○	○	○	○	○

Q27 Your race

- ○ Asian (1)
- ○ Black or African American (2)
- ○ Hispanic or latino (3)
- ○ Native American/ Pacific Islander (4)
- ○ White (5)
- ○ Prefer not to answer (6)

Q68 What is your nationality (what nation are you from?)

____

Q28 Your sex

- ○ Male (1)
- ○ Female (2)
- ○ Other (3)

Q29 Year you were born

____

Q30 If you have questions or comments about this survey or this study you may type them here. (This is optional)

____

End of Block: INTEREST AND CONFIDENCE

Appendix 3

Cellverse Fall 2019 Sept 9 Post Cell conceptions

Start of Block: Gaming Questions

Start of Block: BACKGROUND

Q109 **CELLVERSE SURVEY**
Please answer the following questions to the best of your ability.

Name Please type your ID for the study here. (If you do not know your ID, type your name and we will replace it).

____

____

____

____

____

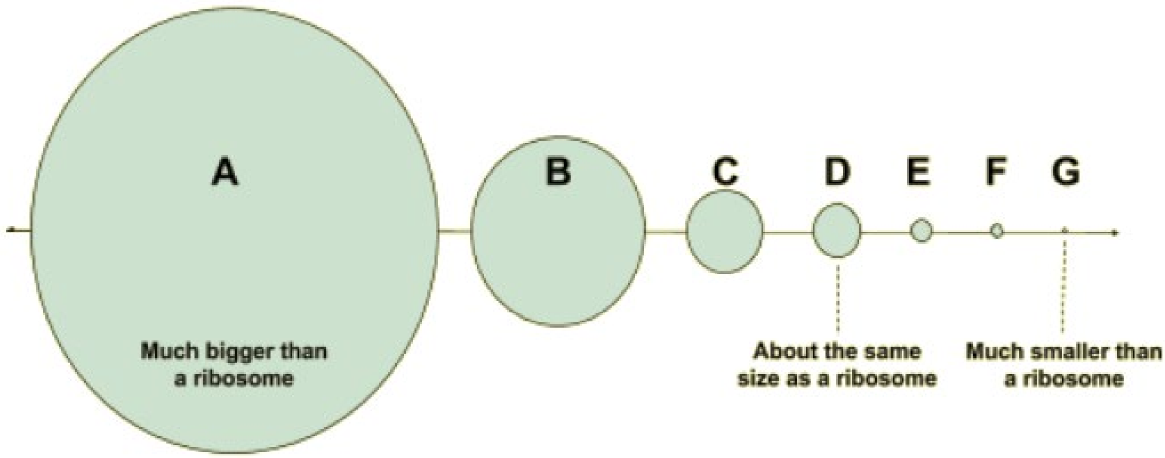
Q24
PARTS OF A CELL
Please answer the following questions to the best of your ability.

Q12 Here is a list of items that exist in a cell. Drag and drop to put them in order of 1 largest to 9 smallest. Put #1 at the top of the list.

______ mitochondria (1)
______ nucleus (2)
______ endoplasmic reticulum (3)
______ tRNA (4)
______ Golgi body (5)
______ water molecule (6)
______ ribosome (7)
______ atom (8)

Page Break

Size: Please answer the following questions to the best of your ability. Please don't look anything up - we want to know what you know right now.



Here is a diagram with general sizes of different items in a cell. "D" is about the size of a ribosome. In the game, the FR3ND character was also the size of a ribosome.

Choose a circle (A-G) that's about the same size as the part of the cell in the list below (mRNA, Translocation channel....).

	same size as A (1)	same size as B (8)	same size as C (2)	same size as D (3)	same size as E (4)	same size as F (5)	same size as G (6)
Nucleus (1)	○	○	○	○	○	○	○
mRNA (2)	○	○	○	○	○	○	○
lysosomes (3)	○	○	○	○	○	○	○
amino acids (4)	○	○	○	○	○	○	○
Proteins (5)	○	○	○	○	○	○	○
Ions (6)	○	○	○	○	○	○	○

Number: Give your best guess of how many of each organelle below would exist in a human lung cell.

	1 of the organelle (1)	2-5 organelles (2)	6-50 organelles (3)	51-200 organelles (4)	over 200 of the organelles (5)
Nuclei (1)	○	○	○	○	○
Ribosomes (2)	○	○	○	○	○
Mitochondria (3)	○	○	○	○	○
Proteins (4)	○	○	○	○	○
Smooth ERs (5)	○	○	○	○	○
Vacuoles (6)	○	○	○	○	○
Centrioles (7)	○	○	○	○	○

Estimate: Now try to give a number estimate of how many ribosomes would exist in the cell. (Please estimate an actual number).

____

Page Break

Q15
CELL ORGANELLES: Please answer the following questions to the best of your ability. Please don't look anything up - we want to know what you know right now.

Q16 These organelles use RNA to string together amino acids and create proteins, which are essential for cell functions.

- ○ Nucleus (1)
- ○ Golgi body (2)
- ○ Ribosome (3)
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- ○ Nucleus (1)
- ○ Mitochondria (2)
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Q19 These organelles keep the cell clean by breaking down cellular waste.

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- ○ Golgi body (3)
- ○ Vacuole (4)

Q20 This organelle encloses the genetic information used by the cell to make proteins.

- ◯ Lysosome (1)
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Q41 This organelle forms a stable twisted structure that connects adjacent cells together.

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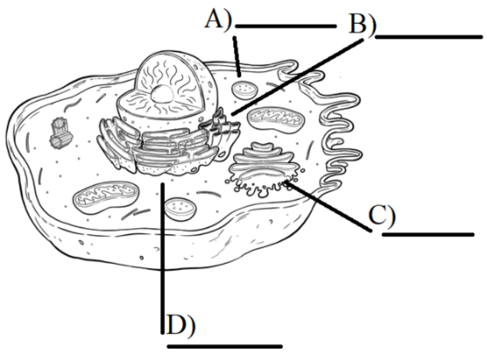
Q43 Below is an image of a cell from a textbook. Based on the image below, which organelle packages and distributes proteins to the rest of the cell? Label the organelle of your answer.



◯ Area A (1)

◯ Area B (2)

◯ Area C (3)

◯ Area D (4)

Q45 The image of a cell in the question above is not entirely accurate. What suggestions would you make to make the cell more realistic?

____

Page Break

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______ CFTR protein is folded inside the ER (3)

______ mRNA encounters ribosome (4)

Q49 During translation, the ________ is sandwiched between the two halves of the ________. At that point, the ________sequences are decoded from nucleotides.

- a. DNA; tRNA; amino acid (1)
- b. mRNA; tRNA; amino acid (2)
- c. mRNA; ribosome; amino acid (3)
- d. DNA; ribosome; mRNA (4)

Q50 Where in the cell does the majority of translation occur?

- a. Nucleus (1)
- b. Mitochondria (2)
- c. Ribosome (3)
- d. Endoplasmic Reticulum (4)

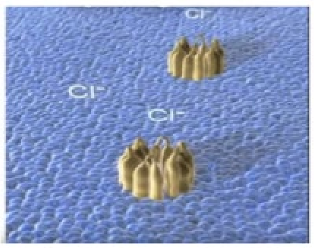
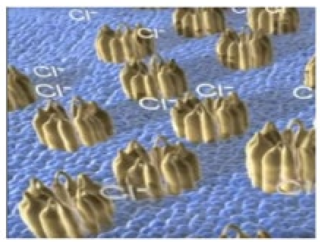
Q102 What happens at a translocation channel?

- ◯ RNA moves out of the nucleus (1)
- ◯ Proteins move across the cell membrane (4)
- ◯ RNA is converted to amino acid chains (5)
- ◯ Proteins move through the Golgi Body (6)

Page Break

Q52 Membrane: Please choose one answer for the following questions unless otherwise instructed.

Q53 The image to the left depicts a low density of CFTR channels, whereas the one to the right depicts a healthy density of proteins on the cell membrane. Why would a low density of channel proteins on the membrane be problematic?

○ a. Low density of proteins yields no transfer of Cl ions (1)

○ b. Low density of proteins yields little transfer of Cl ions due to its abnormal openings of channels (2)

○ c. Low density of proteins means the viscosity of the lung's mucus is abnormal (3)

○ d. Low density of proteins means the cell membrane is destroying protein channels (4)

Q56 You have detected 0 CFTR proteins on the cell membrane. What might have caused this issue?

○ a. closed protein channels (1)

○ b. inconsistent DNA transcription (2)

○ c. misfolded proteins (3)

○ d. slightly closed translocation channels (4)

Q57 Why is having enough protein channels on the membrane important?

- a. it allows enough transfer of sodium ions (1)
- b. it prevents mucus from being too thick and sticky to move out of the lungs (2)
- c. it allows enough transfer of chloride ions (3)
- d. both b and c (4)
- e. all of the above (5)

Page Break

End of Block: BACKGROUND

Start of Block: Spatial Questions

Q70 **<u>GLOSSARY</u>** **Spatial:** describes how objects fit together in space
Spatial Orientation: the ability to identify the position or direction of objects or points in space.
Spatial Navigation: the process to determine the route to a goal and then travel that route.

Q72 MENTAL WORKLOAD IN SPATIAL ACTIVITIES
These questions were adapted from the NASA-TLX. Please answer the following questions to the best of your ability.

Q76 How much mental activity was required while navigating and/or orienting in the game?

	Low mental activity	High mental activity
	0 1 2 3 4 5 6 7 8 9 10	
1 ()		

Q78 Were the tasks you were asked to perform easy or complex?

	Easy	Complex
	0 1 2 3 4 5 6 7 8 9 10	
1 ()		

Q80 **PHYSICAL DEMAND**

Q82 How much physical activity was required while navigating and/or orientating in the game?

	Low physical activity	High physical activity
	0 1 2 3 4 5 6 7 8 9 10	
1 ()		

Q84 Were the tasks you were asked to perform easy or complex?

	Easy	Complex
	0 1 2 3 4 5 6 7 8 9 10	
1 ()		

Q86 **TEMPORAL DEMAND**

Q88 Did you feel any time pressure while navigating and/or orienting in the game?

	Low time pressure	High time pressure
	0 1 2 3 4 5 6 7 8 9 10	
1 ()		

Q90 Was the pace too slow or fast?

	Too Slow	Too Fast
	0 1 2 3 4 5 6 7 8 9 10	

1 ()	

Q92 **OVERALL PERFORMANCE**

Q94 How successful were you at navigating and exploring in the game?

	Low						High				
	0	1	2	3	4	5	6	7	8	9	10
1 ()											

Q96 How satisfied are you with your performance?

	Low						High				
	0	1	2	3	4	5	6	7	8	9	10
1 ()											

Q98 **EFFORT**

Q100 How hard did you have to work to accomplish your level of performance in spatial navigation and orientation?

	Low						High				
	0	1	2	3	4	5	6	7	8	9	10

1 ()	

Q102 **FRUSTRATION LEVEL**

Q104 How irritated, stressed, and/or annoyed versus content, relaxed, and/or complacent did you feel while navigating and/or orientating?

	Low									High	
	0	1	2	3	4	5	6	7	8	9	10
1 ()											

Page Break

Q106 SPATIAL SITUATION MODEL: These questions are a subscale adapted from the MEC Spatial Presence Questionnaire (Vorderer et al., 2004). Please answer the following questions to the best of your ability.

Q100

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
I was able to imagine the arrangement of the spaces presented in the game very well. (1)	○	○	○	○	○
I had a precise idea of the spatial surroundings presented in the game. (2)	○	○	○	○	○
In my mind's eye, I was able to clearly see the arrangement of the objects presented/described. (3)	○	○	○	○	○
I was able to make a good estimate of the size of the presented space. (4)	○	○	○	○	○
I was able to make a good estimate of how far apart things were from each other. (5)	○	○	○	○	○
Even now, I still have a concrete mental image of the game's spatial environment. (6)	○	○	○	○	○
Even now, I could still draw a plan of the spatial environment in the game. (7)	○	○	○	○	○
Even now, I could still find my way around the spatial environment in the game. (8)	○	○	○	○	○

Q108 SPATIAL PRESENCE: SELF LOCATION

These questions are a subscale adapted from the MEC Spatial Presence Questionnaire (Vorderer et al., 2004). Please answer the following questions to the best of your ability.

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
I had the feeling that I was in the middle of the action rather than merely observing. (1)	○	○	○	○	○
I felt like I was a part of the environment in the game. (2)	○	○	○	○	○
I felt like I was actually there in the environment of the game. (3)	○	○	○	○	○
I felt like the objects in the game surrounded me. (4)	○	○	○	○	○
It was as though my true location had shifted into the environment in the game. (5)	○	○	○	○	○
It seemed as though my body was present in the environment of the game. (6)	○	○	○	○	○
I felt as though I was physically present in the environment of the game. (7)	○	○	○	○	○
It seemed as though I actually took part in the action of the game. (8)	○	○	○	○	○

	Strongly disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)
I had the feeling that I was in the middle of the action rather than merely observing. (1)					
I felt like I was a part of the environment in the game. (2)					
I felt like I was actually there in the environment of the game. (3)					
I felt like the objects in the game surrounded me. (4)					
It was as though my true location had shifted into the environment in the game. (5)					
It seemed as though my body was present in the environment of the game. (6)					
I felt as though I was physically present in the environment of the game. (7)					
It seemed as though I actually took part in the action of the game. (8)					

End of Block: Spatial Questions

Start of Block: Block 1

Q31 Now, a few questions about you.

Q63 How confident are you that you can do the following:

	Not at all confident (1)	Not confident (2)	Neither confident nor unconfident (3)	Confident (4)	Completely confident (6)
Figure out the reasons why things happen in nature (1)	○	○	○	○	○
Use tables and graphs to figure things out. (2)	○	○	○	○	○
Figure out the relationships between organisms and environments. (3)	○	○	○	○	○
Look at data that I collect and see how it fits together. (4)	○	○	○	○	○
Connect the things that I am learning about in science with what I already know. (5)	○	○	○	○	○
Select "not at all confident" for this line so we know you're paying attention. :) (7)	○	○	○	○	○

Q65 Share the following with us

	Strongly disagree (1)	Disagree (2)	Neither agree nor disagree (3)	Agree (4)	Strongly agree (5)
I find science enjoyable (1)	○	○	○	○	○
Science is just not interesting to me (2)	○	○	○	○	○
I like doing work in my science class (3)	○	○	○	○	○
I like learning new things in science (4)	○	○	○	○	○
In general, I find working on science assignments to be interesting (5)	○	○	○	○	○

Q64 How confident are you that you can ...

	Not at all confident (1)	Not confident (2)	Neither confident nor unconfident (7)	Confident (8)	Completely confident (9)
Do the kinds of things that scientists do. (1)	○	○	○	○	○
Solve the kinds of complicated problems that scientists have to solve. (2)	○	○	○	○	○

Q66 Share the following with us

	Strongly disagree (1)	Disagree (2)	Neither agree not disagree (3)	Agree (4)	Somewhat agree (5)
My seeing and hearing senses were used fully in this simulation game. (1)	○	○	○	○	○
I lost track of events happening in the real world while I used this simulation. (2)	○	○	○	○	○
I felt like I was really there. (3)	○	○	○	○	○
It was easy to concentrate on the simulation. (4)	○	○	○	○	○
I felt like I became more skilled in the simulation as I went. (5)	○	○	○	○	○

Q30 Questions or comments about this survey (optional)

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End of Block: Block 1

Appendix 4

Cellverse Data Entry Spring 2020

Start of Block: ID and consent

Q1 Type participant ID here (month-date-time) add Y if using head set and N if not.

____

Q2 **Introduction**
Thank you for helping us with this study. First we will review a consent form, then do a preassessment, have you do some drawing, play the game, and then a post assessment. We will send you a very short questionnaire via email in one week to see what (if anything) you remember. Once you have completed that we will send you a $10 gift card to Amazon.

Q3 **Part 1: Consent**
Here is the consent form. Remember that the study is optional and you can withdraw at any time. The information you provide is confidential, we won't use your name with your data.If you have questions or concerns, you can contact meredith@mit.edu, or the IRB office. I’ll give you some time to read the consent form, and you can ask questions.

☐ Consent completed (1)

End of Block: ID and consent

Start of Block: Preassessments

Q4 Part 2a. Draw a cell: Please take 5 minutes to draw a cell. Draw as much as you remember, and label what you can. We will talk about this after you play the game. (When they are finished, ask) Where did you get your ideas about cells? (Type notes below).

____

Q5 Part 2b. Sketch out Translation: Please take 3 minutes to sketch what you remember about the translation process. Draw as much as you remember, and label what you can. (When they are finished, ask) Please talk through your diagram. (Type notes below)

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Q6 Part 3: Take the Presurvey: Before we tell you more about the game, we're going to give you this pretest to see what you know and gauge where you are. (write down time they started presurvey)

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End of Block: Preassessments

Start of Block: Game play

Q7 Part 4 (INTERNAL): Briefly show them what they will be able to do Introduction to the game (3 min) - Start the game and very briefly show them what they will be able to do. Just show them that they will be able to move, select, use a clipboard, and use the dashboard. Tell them they will receive specific instructions during the game tutorial.

Q9 Part 5 (INTERNAL): Start the game and let them do the tutorial. Remind them that their goal is to use clues to figure out what is wrong with the cell. First we would like you to explore the cell (Record start time below)

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Q8 Part 5a: Exploring the cell.(After the tutorial, ask them)
OK, now I would like to have you try finding things in the game.

Q10 Please find a lysosome (record seconds until task completion).

Q11 Please find a mitochondria (record seconds until task completion)

Q12 Please find the nucleus (record seconds until task completion)

End of Block: Game play

Start of Block: Observing game play

Q13 Part 6 - Start inquiry/ Guide in nano: Observe as they play. (If they have not started the inquiry 15 minutes after they started, then tell them) "Remember that the goal of the game is to figure out what's wrong with the cell. To start that process, press Y and push the start button on the lower left hand corner".

Q14 If they did not start the inquiry after 15 minutes of game play, guide them to open the dashboard and press "start" on the lower right hand corner.

____

Q15 (Make sure they are in nano. Then say)"See if you can find a green thing that looks like a rope. What is it? What is it doing? See if you can go through the blue window like things. What is the window called? What is on the other side?" You may type notes below.

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End of Block: Observing game play

Start of Block: Post assessments

Q17 Part 7 - After game - route knowledge: Wonderful - you have finished the game! We have a few post assessments we would like you to do. Exit out of the game, get back into the game, and skip the tutorial by pressing "p" until it's complete.

Q18 (Start a timer) Please navigate to a lysosome. (measure time to task completion in seconds)

____

Q20 (Start a timer) Please navigate to the nucleus. (measure time to task completion in seconds)

____

Q21 (Start a timer) Please navigate to the endoplasmic reticulum and go into the nano view. (measure time to task completion in seconds)

____

Q23 (Start timer - In nano) Navigate to the mRNA and take a sample. (write down time to task completion in seconds).

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Q24 (Start timer - in nano) Navigate to the amino acid chain and take a sample. (write down time to task completion in seconds).

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End of Block: Post assessments

Start of Block: Post assessment

Q25 Part 8 - Post assessment: Please take the online post assessment.

Q26 Part 9 - Draw a cell(Tell them) Now take three minutes and draw a cell based on what you saw in the game. How would you draw it differently? (Start time - end after 3 minutes - Type notes into the text box. Don't worry about transcribing it verbatim - just type some brief notes).

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Q28 Did your ideas change about how crowded the cell is?

○ Cell is more crowded than I originally thought (1)
____

○ Same amount of crowding as I thought at the start (2)
____

○ Cell is less crowded than I originally thought (3) ____

Q32 How did your ideas change about the size of organelles in the cell?

○ Organelles are different sizes than I thought (1) ____

○ No change in my thinking (2) ____

○ I didn't have any sense of sizes (3) ____

Q27 Did your ideas change about the number of mitochondria in the cell?

○ More mitochondria than I originally thought (1) ____

○ Same amount (2) ____

○ Fewer mitochondria than I originally thought (3) ____

End of Block: Post assessment

Start of Block: Translation

Q33 Part 9b – Translation (Tell them) Now, sketch the process of translation. Tell me how your ideas changed because of the game. (Type brief notes)

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Q29
Did you learn anything about how ribosomes function from the game? Explain briefly.

- ○ Yes (1) ____________________
- ○ No (2) ____________________

Q30
Did you learn anything about how the endoplasmic reticulum functions from the game? Explain briefly.

- ○ Yes (1) ____________________
- ○ No (2) ____________________

Q34 Did the game give you a better mental picture of what is going on in the cell?

- ○ Yes (1) ____________________
- ○ No (2) ____________________

End of Block: Translation

Start of Block: Thank you!

Q41 Part 11 (internal) - Coding of cell pictures - please do right after the sessionCheck if you saw any of the following in the pictures

- ▢ Post drawing is more detailed than pre drawing (1)
- ▢ Post drawing includes more organelles than pre drawing (2)
- ▢ Post drawing includes a representation of a smaller/ nano view (3)
- ▢ Pre drawing has more labeled organelles than post drawing (4)

Q36 Part 10 - Comments and thank you!Do you have any comments for us about the game? (Type so we have a general sense - we will not transcribe these)

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____

Q37 Thank you for your help testing the game! We will send you a very short post survey in a week - once you respond to those questions we will send you a $10 gift card to Amazon. Thank you!!!

Q43 Anything else we should notice about the cell drawing?

____

Q42 Part 12 (internal) - Coding of translation process - please do right after the sessionCheck if you saw any of the following in the pictures

- [ ] Post drawing is more detailed than pre drawing (1)
- [ ] Post drawing includes more organelles than pre drawing (2)
- [ ] Post drawing includes a representation of a smaller/ nano view (3)
- [ ] Post drawing includes ribosomes (4)
- [ ] Post drawing includes translocation channel or ER representation (5)
- [ ] Post drawing includes amino acids (6)

Q44 Anything else we should notice about the transcription drawing?

____

Q45 What did you notice about gameplay? (check all that apply)

- ▢ Participant said "cool" or "wow" at any point during the game (1)
- ▢ Participant exclaimed "oh" in surprise at one or more points during game (4)
- ▢ Participant smiled or showed evidence of enjoyment. (5)
- ▢ Participant was frustrated about the game (7)
- ▢ Frustration with the controls (3)
- ▢ Participant talked about being/ feeling lost (8)
- ▢ Click to write Choice 7 (6)

End of Block: Thank you!

Start of Block: Analysis of cell drawings

Start of Block: Block 8
