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ABSTRACT

IMPACT OF USER TRAVERSAL ON PERFORMANCE OF STEM LEARNERS IN IMMERSIVE VIRTUAL ENVIRONMENTS

by
Eric W. Nersesian

The emerging technologies of augmented and virtual reality (AR/VR) may have vast implications to societal communication and representation of information. AR/VR computer interfaces are unique in that they may be placed spatially around the user in three-dimensional (3D) space; this affords new methods of both presentation and user interaction with the target information.

This may be especially impactful in the education of science, technology, engineering, and mathematics (STEM) professionals. Prior research has shown that simulations and visualizations improve the performance of STEM learners compared to live instruction and textbook reading. Yet, research into AR/VR as a learning environment for widespread educational applications remains limited.

To address this research gap, this dissertation examines a fundamental AR/VR interface capability, the ability for the user to traverse a virtual environment, and its impact on learning. The first study of the dissertation compares the performance of STEM learners within a physical and a virtual learning environment, both non-traversable. Evidence from this study suggests that a non-traversable AR/VR interface offers comparable learning efficacy to a traditional physical environment.

The second study of the dissertation compares the performance of STEM learners in a non-traversable physical environment against STEM learners in a traversable virtual environment. Similar to the first study, evidence from this study suggests that instructional delivery in a virtual environment with a traversable AR/VR interface offers comparable learning efficacy to a physical environment.

The first two studies of the dissertation suggest that AR/VR computer interfaces, both with and without user traversal, offer comparable learning efficacy to their physical environmental equivalents. The final study of the dissertation compares the performance of STEM learners using the same virtual environment, but alters the traversal ability between the two groups. Evidence from the third study suggests that altering the user traversal of an AR/VR interface did positively impact its learning efficacy. This dissertation offers evidence that AR/VR technologies, with and without user traversal, are suitable STEM learning environments. Additionally, AR/VR technologies provide higher levels of traversal capabilities which may serve to increase learning performance.

**IMPACT OF USER TRAVERSAL ON PERFORMANCE OF STEM
LEARNERS IN IMMERSIVE VIRTUAL ENVIRONMENTS**

by
Eric W. Nersesian

**A Dissertation
Submitted to the Faculty of
New Jersey Institute of Technology
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Doctor of Philosophy in Information Systems**

Department of Informatics

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APPROVAL PAGE

**IMPACT OF USER TRAVERSAL ON PERFORMANCE OF STEM
LEARNERS IN IMMERSIVE VIRTUAL ENVIRONMENTS**

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The emerging technologies of augmented and virtual reality (AR/VR) may have vast implications to societal communication and representation of information [44]. Similar to the introduction of the personal computer and the internet, AR/VR may open up new forms of information visualization, manipulation, and communication [83]. This may be especially impactful in the education and productivity of professionals, as research shows simulations and visualizations improve science, technology, engineering, and mathematics (STEM) learner performance and engagement [100].

Data modeling and programming complexity of STEM professions are growing as their fields become more computational-based. AR/VR interfaces may become necessary in the STEM fields to manage the higher levels of sensory-processing, cognitive, and decision-making capabilities required to interact with more complex computer systems and data sets [60]. Monitor-based interfaces may be replaced by AR/VR as user interactions require three dimensions to increase information bandwidth between users and computer systems.

Monitor-based educational technologies, such as simulations, animations, and video games, have been well explored as STEM learning environments [30, 61]. While AR/VR educational technologies are still in their infancy, they show a strong inclination towards improving education [48], collaboration [77], and productivity [12]. AR/VR has the potential to increase learner immersion [97], allowing the user to interact directly with a simulation and focus on the information presented to them.

Learners using educational technologies, e.g., websites, interactive simulations, and educational video games, have shown improvements in abstract reasoning,

spatial cognition, and multitasking abilities compared to traditional educational media, e.g., textbooks, illustrations, and videos. [8]. These abilities are essential for modern educational approaches [7], and has led the United States Office of Educational Technology to call for the integration of immersive technologies into public schools [86]. Current pedagogical methods of in-person and textbook instruction will need to be supplemented, especially for students entering STEM fields since they are more likely to be engaged with higher-end technologies [35].

Examining AR/VR's impact on STEM education through the fields of learning science and human computer interaction (HCI) allow for unique understanding of how these emerging technologies will impact our knowledge-based society. Identifying STEM educational use cases of AR/VR may help scope research efforts, and improve technology efficacy, since there is a lack of research into AR/VR as a learning environment for widespread educational applications [13]. virtual reality (VR) is an excellent starting point to investigate design frameworks that can be generalized for the wider range of AR/VR headsets [60]. Current wireless VR headsets are an affordable self-contained medium to conduct HCI research, where results can be generalized to identify research and design practices for AR/VR as a general computing platform.

1.2 Goals

To help define the understudied area of AR/VR use cases in STEM education, this dissertation will examine one fundamental AR/VR capability, *virtual environmental traversal*, and its impact on users' learning performance. As the common body position while learning for a student is to be seated for live instruction, use cases of AR/VR educational technology will need to be compared in the same seated manner for the user. This limits the students ability to traverse and interact with their environmental surroundings, which in turn limits the potential for embodied cognition

and embodied interactions in physical teaching and educational technology solutions (see Section 2.4). AR/VR is, currently, the only computer interface which affords the user environmental traversal capabilities. Since this is a relatively new research area, little is known about how environmental traversal impacts user learning performance in AR/VR. Future studies will need to continue this path of exploration into areas of live instruction where the student is in an active, learn-by-doing physical environment and identify what benefits AR/VR educational technology may contribute with these expanded set of user interactions.

The goal of educational technology is not to replace live instruction but to ensure that comparable alternative learning opportunities are available when live instruction needs to be supplemented to keep the learning potential high for the student. As AR/VR is currently the only educational technology that offers the user environmental traversal, it is important to compare AR/VR against live instruction with and without the user ability to traverse their environment. It is also important to compare different environment traversal interactions within AR/VR to see if there is an learning impact across learning mediums (live instruction vs AR/VR) and within AR/VR traversal interactions (different traversal methods and styles).

The first goal of this dissertation is to understand the efficacy of AR/VR against live instruction without the AR/VR users' ability to traverse the virtual environment. This is because the common learning arrangement for a student is to be seated, and not moving from that position, it will be important to understand how a non-traversable AR/VR learning environment impacts user performance compared to a seated learning situation. As a supplemental educational technology, non-traversable AR/VR learning environments' efficacy would need to be verified, and it would need to be understood how it impacts a user's perceptions of their learning material.

The second goal of this dissertation is to understand the efficacy of AR/VR against live instruction with the AR/VR users' ability to traverse the environment.

Although it is common for students to be seated and not moving from that position while learning, that is not always the case in live instruction, and it may be necessary to allow the learner to move throughout their environment may help them learn the subject matter. It would be important to understand how a traversable AR/VR learning environment impacts user performance and compare this to a seated physical learning environment. As a supplemental educational technology, traversable AR/VR environments' efficacy would need to be verified. It would need to be understood how traversing an environment instead of being in a seated or passive position helps with learning performance. This knowledge may indicate that alternative learning methods could have increased efficacy when allowing a level of mobility for the learner during the learning process.

The third and final goal of this dissertation is to understand the impact of varying the method of the AR/VR environmental traversal interaction. Although it is common for students to be in a seated position while learning, it is not a universal learning condition. In fact some learning situations require a mobile learner such as a physical laboratory experiment requiring the learner to move around the laboratory table while they interact with laboratory equipment. As a supplemental educational technology, traversable AR/VR environments' efficacy would need to be verified based on the users' ability to traverse the virtual environment. Different styles and types of traversal interactions would need to be examined and their impacts to user performance and usability preferences understood. Since this is an initial exploration into studying the various methods of AR/VR environmental traversal interaction, a straight forward test would involve comparing the most natural traversal method available with the technology against a more limited form of the same traversal method. This means that one interaction method would be for the user to walk through the virtual environment exactly as the user would in a physical environment,

and the other interaction method would be for the user to use a controller device (e.g., a keyboard or gamepad) to move the virtual environment around their stationary self.

1.3 Research Statement and Questions

AR/VR technologies show strong potential as the next-generation computer interface for the education, collaboration, and productivity of STEM professionals. The dissertation examines a fundamental AR/VR interface capability, the ability to traverse a virtual environment, and its impact upon learning performance within STEM education. The first research initiative examines whether STEM learners gain the same benefits towards their academic performance regardless of whether they receive training in a physical or virtual environment, while in a stationary position. The second research initiative examines if a traversable virtual environment could have the same benefits as live lecture in a physical environment with the learner in a stationary position. The final research initiative is to understand how the traversal characteristics of a spatial interface in a virtual environment influences users' STEM learning performance.

The research questions that arise from this research statement are:

1. How does a non-traversable AR/VR environment impact learner performance?
 - (a) Is non-traversable AR/VR environment as effective as in-person instruction?
 - (b) How does a non-traversable AR/VR environment impact user perceptions?
2. How does a traversable AR/VR environment impact learner performance?
 - (a) Is a traversable AR/VR environment as effective as in-person instruction?
 - (b) How does a traversable AR/VR learning environment impact usability?
3. How does body kinematics of AR/VR traversal impact learner performance?
 - (a) How does body kinematics of AR/VR traversal impact learning?

- (b) How does body kinematics of AR/VR traversal impact retention?
- (c) How does body kinematics of AR/VR traversal impact usability?
- (d) How does body kinematics of AR/VR traversal impact task time?

1.4 System and Stimuli Prototyping

The limitation of software options for AR/VR educational technologies restricted the ability to conduct in-depth studies on isolating user traversal factors on the efficacy of a virtual learning environment. The study for the first research question used off-the-shelf software with a non-traversable environment, while the studies for the following two research questions used custom-built prototypes to allow traversal of the virtual learning environment. Once the prototype was built, the second research question's study (see Section 4.3) compared the educational efficacy of a traversable immersive virtual learning environment in comparison to an instructor-led lecture. The prototype was then expanded for the third research question's study to isolate the impact of traversal ability on learning, retention, task time, and engagement.

The immersive virtual learning environments used in the second and third research questions' studies were designed to teach the introductory computer science (CS) topics, binary counting and a sorting algorithm, bubble sort, to CS novices. The AR/VR educational software built from the prototyping process in the lab is called CSpresso, and is designed for students to learn at their own pace in an effort for them to internalize concepts that produce measurable learning outcomes. The prototype was designed to simulate learning situations usually found in physical learning environments, and can engage and measurably teach STEM concepts to a wide range of learners just as effectively as in a physical learning environment (see all Figures in Appendix H and I).

1.5 Overview of the Studies

Examining AR/VR's impact on STEM education through the fields of learning science and HCI allow for unique understanding of how these emerging technologies will impact our knowledge-based society. Identifying STEM educational use cases of AR/VR may help scope research efforts, and improve technology efficacy, since there is a lack of research into AR/VR as a learning environment for widespread educational applications [13]. To address this research gap, this dissertation examines a fundamental AR/VR interface capability, the ability to traverse a virtual environment, and its impact on learning.

The first study of the dissertation compares the performance of STEM learners within a physical and a virtual learning environment, both with no environmental traversal abilities afforded to the learners. Learners in the physical environment were seated during their learning experience. Learners in the virtual environment had their entire AR/VR interface within reaching distance of their seated position. Evidence from this study suggests that instructional delivery in a virtual environment with no traversal of the spatial AR/VR interface offers comparable learning efficacy to the physical traditional environment.

The second study of the dissertation compares the performance of STEM learners seated in a physical environment against STEM learners in a virtual environment that required them to traverse the spatial AR/VR interface. Evidence from this study suggests that instructional delivery in a virtual environment with required traversal of the AR/VR interface offers comparable learning experiences to the physical equivalent. Additionally, the evidence suggests that AR/VR interfaces with environmental traversal interactions can offer high user engagement as an effective supplement to traditional physical learning environments.

The final study of the dissertation compares the performance of STEM learners using the same virtual learning environment, but alters the environmental traversal

ability between the two groups. It compares the efficacy of a natural walking traversal method to a hand controller-based traversal method on learning performance of the subjects. Evidence from this study suggests that the more embodied traversal interaction of natural walking offers better learning, retention, usability, and task time performance to its users.

The first and second studies of the dissertation show that AR/VR computer interfaces, both with and without user traversal ability, offer capable learning efficacy to their physical environmental equivalents and can offer higher engagement, increased learning metrics, and enable alternative learning methods. Once it was shown that AR/VR computer interfaces, both with and without user traversal, can have comparable efficacy to traditional learning methods, the third study looked at how altering the user traversal ability on the same AR/VR computer interfaces impacted its learning efficacy. It was shown that the more embodied traversal of natural walking across a spatial AR/VR interface may have strong impact on the technology's learning efficacy. This dissertation offers evidence that AR/VR technologies, with and without user traversal, are suitable STEM learning environments. Additionally, providing higher levels of traversal capabilities may increase learning performance.

CHAPTER 2

RELATED WORK

2.1 Introduction

This chapter reviews the prevailing theories and models of human cognition from the fields of educational psychology, the learning sciences, human factors, and HCI. This review of human cognitive models will be necessary to identify areas of research that may offer insights to effectively design for AR/VR educational technology. The chapter will conclude with a review of the current state of educational technology use cases in STEM education that identifies learning challenges appropriate for AR/VR educational technology. Conducting research in these areas may indicate STEM education use cases in AR/VR educational technology that represent an immediately comparable domain for measuring the likelihood of AR/VR educational technology benefits for education as a wider field.

2.2 Cognitive Constructivism in the Learning Sciences

Many psychologists use Piaget's Theory of Cognitive Development and Vygotsky's Socio-cultural Perspective as frameworks for cognitive development [124]. Piaget argued that human cognitive processes change slowly but drastically over their lifetime because humans are constantly making sense of the world around them [90]. He identified four factors that influence cognitive processes: biological maturation, activity, social experiences, and equilibration [90]. These factors tend to push thought processes toward organization and adaptation. Organization refers to the constant combining and arranging of behaviors and thoughts into coherent systems, which is what most people will think of in regards to education. Adaptation refers to the adjustment of behaviors and thoughts to the environment, which indicates that

environment factors may be an important consideration for both physical and virtual learning environments.

While Piaget examined how cognition developed internally at an individual level, Vygotsky examined how cognition developed both internally to an individual and externally within a culture. It is recognized today by psychologists that the processes and content of thinking is shaped by culture [124]. Vygotsky believed that cognitive activities in humans occur in a cultural context and cannot be understood by itself [56]. He argued that cognitive structures and processes can be connected to that individual's social interactions, and that these interactions have active influence on the creation of these thinking processes [56]. This suggests that cultural conditions in which learning occurs are factors that should be taken into account when designing physical and virtual learning environments to maximize their potential.

The previously discussed cognitive development theories have led to an interdisciplinary approach to understanding learning, called the learning sciences, involving philosophy, sociology, psychology, education, and neuroscience research [124]. Professionals in the learning sciences, regardless of their background, are interested in how expert-level knowledge in subjects like science, literacy, and mathematics is acquired and applied by professionals such as scientists, writers, and mathematicians [124]. Even though different learning science approaches and perspectives exist to study cognitive development, there is common acknowledgement of some learning fundamentals, which are: experts have deep conceptual knowledge, learning must come actively from the learner, and reflection is necessary to develop deep conceptual knowledge [102]. It is acknowledged by learning science professionals that these fundamentals must be practiced with live instruction and supplemental mediums, such as educational technologies, for learners to gain the deep conceptual knowledge allowing them to become experts [124].

The acknowledged learning fundamentals form a broad term in the learning sciences, called Constructivism. A standardized constructivist theory of learning does not currently exist, but there are two core ideas to most constructivist theories [124]. The first idea, called individual constructivism, is that learners are active in constructing their own knowledge, which centers on Piaget's theories [124]. The second idea, called social constructivism, is that social interactions are important in this knowledge construction process, which centers more on Vygotsky's theories [16]. Pedagogical practices in STEM education, and educational technology all embrace constructivist ideas in varying mixtures [124]. Constructivist theories are a useful framework to connect the domains of learning science and HCI necessary for designing AR/VR educational technologies. AR/VR can enable users to freely roam through 3D visual representations of learning objectives, interactions, and environments. While roaming throughout the virtual learning environment, users can be encouraged to interact with the simulation through physical input devices to allow the process of actively construct their own knowledge as stated by constructivist theories.

2.3 Cognitive Models in Human Computer Interaction

When designing a new 3D interaction device or technique, it is important to consider the human factors that affect its usability and performance [60]. For proper evaluation of usability and performance, it is important to have a basic knowledge of how users process information into useful interactions. When a user interacts with a system, they perceive information from all available sources from the system, process that information in various forms, and take actions based on decisions they made on the information made available to them [60]. The system will return information back to the user that they receive as feedback on their actions, and this starts the beginning of a new cycle in the information-processing loop [60]. Similar to how a teacher would build this information-processing loop into their classroom interactions for effective

learning of their students, designers of AR/VR educational technologies need to be keenly aware of how the virtual learning environment is interacting with the user.

Wickens and Carswell introduced a high-level model of mapping the information processing to three main factors: perception, cognition, and physical ergonomics [121]. In the Wickens and Carswell model, stimuli is perceived by the user capable of interpreting it meaningfully based on past experiences. The user may choose to respond to the perception by choosing and executing on actions based on their cognition, which is a key aspect of the user interaction [121]. Knowledge gathered from perceptions are generally regarded from the user's perspective as coherent, justified, and true [51]. Cognition is the primary generator of knowledge from the users' attention on their perceptions, and governs processes in memory, language, and thought [51]. Designing proper educational technology requires particular attention to this information processing loop and how it can influence user cognition of perceptions that the system presents to the user.

Information processing models, like Wickens and Carswell's idea, usually represent discrete, minute information events occurring during system interactions. In contrast to these models, user action models portray high-level system interactions by the user consisting of four aspects: goals, execution of physical actions, system outcomes of those actions, and outcome evaluations [60]. Norman's Seven Stages of Action was one of the first well-known user action models as he defined stages of user interactions with a system. He studied the structure of actions, and identified the four mentioned aspects: "the goal, what is done to the world, the world itself, and the check of the world" [84]. Abstracting the information processing models to higher levers of system interactions and user actions helps keep the design structure of learning goals clear and consistent for educational technologies.

A user action model that has been designed specifically for 3D user interfaces is the User-System Loop as a system oriented adaption of Norman's Seven Stages of

Action [74]. In this model, user interactions begin with actions that manipulate input devices, which are interpreted as sensory information to the system. The system alters the data and models underlying the simulation of objects, their physical attributes and behavior. The system updates the rendering information going to the system's outputs connecting to the user's inputs based on changes to the simulation's data and models. The information is processed by the user as stimulus to be perceived. The User-System Loop model is a helpful abstraction of the interactions between the user and system hardware interfaces that are common for AR/VR technologies. Identifying frameworks with the correct level of abstraction is helpful for educational technology designers to have enough information about the lower level details of the psychological, educational, ergonomics, and system requirements while keeping their decisions oriented to the higher level goals of the software design requirements.

2.4 Principles of Embodiment Across Learning Sciences and HCI

Recently, Embodied Cognition has become more prevalent in the learning sciences. This is awareness that “the way we think about and represent information reflects the fact that we need to interact with the world” [4]. The interactions humans have with the world around them perceived through their senses and bodies affects their thinking [4]. This means that humans' cognitive processes are deeply connected to their bodies' interactions with the physical world, and that cognition depends on the sensorimotor experiences [4]. Shifting the perspective on cognition allows for viewing the body, not the mind, as the primary motivator of cognition but the mind is still necessary for interactions with the outside world. The relationship of the body to the mind in regards to learning offers insights into the benefits of AR/VR as an educational technology.

Humans' senses and motor functions are essential to their understanding of the world and not just simple channels for the mind to gather audio and visual information

from the world [28]. Understanding how the human body interacts with the world is essential to understanding the mind [28]. An example would be observational learning, where watching a person demonstrate a skill activates the areas of the brain that would be involved in acting the skill themselves. It is similar to the effect of the brain learning the skill by performing it directly [24]. Using objects to act out the skill can support learning, such as using models, gestures, movements, simulations, drama, and re-enactments [24]. Observational learning, and other Embodied Cognition learning scaffolds, are highly reliant on the proper physical environment, participants, and objects to engage these learning methods. AR/VR educational technologies would be well suited as alternative Embodied Cognition learning methods when the proper physical requirements are hard to meet.

The HCI field has a similar theory called Embodied Interaction, which is defined as “interaction with computer systems that occupy our world, a world of physical and social reality, and that exploit this fact in how they interact with us” [26]. Embodied Interaction takes advantage of a user’s familiarity with the real world, including interactions with socializing and physical artifacts [60]. Dourish identifies these real-world familiarities as embodied phenomena, which he describes as objects in existence located in “real time and real space.” Embodied Interaction is “the creation, manipulation, and sharing of meaning through active, and sustained interaction with these embodied phenomena” [26]. This theory is the starting framework to understand how to incorporate 3D user interfaces of AR/VR educational technologies to apply Embodied Cognition learning methods, such as observational learning.

Dourish discusses the concept of Embodied Interaction in the contexts of social and tangible computing [26]. Tangible Computing is the concept of user interactions through physical environments on digital information [45]. Tangible user interfaces integrate physical representations of digital information with the use of physical objects and the physical mechanisms for interacting with them [46]. Interacting

with physical objects allows the user to take advantage of already developed skills for physical interactions with physical world objects [26]. I would extend the definitions of Embodied Interaction and Tangible user interfaces into digital objects represented through AR/VR headsets that can occupy our physical reality as well as physical objects. This would extend the insights of these theories to the capabilities of AR/VR educational technologies as well.

These digital objects would appear overlaid into the user’s physical world, and allow interaction with computer systems for more natural educational technologies that are intertwined with the user’s physical reality without the overhead of using physical objects for the user interface. AR/VR educational technologies using headsets and hand controllers can simulate aspects of the physical objects and environments that may offer learning benefits to STEM education by combining ideas from embodied cognition and embodied interaction. AR/VR educational technologies could be designed to simulate the sensorimotor experiences that a learner would have while using their body to learn about the world around them, and to encourage the user to interact and explore the virtual environment that is presented to them.

2.5 Physical and Virtual Lab Work Contextualizes STEM Education

Issues with contextualizing, effectively demonstrating and visualizing class material is a constant concern for STEM educators, and is characterized as a disconnect between the student’s perspectives and the pedagogical frameworks of the topic [41, 109, 11]. Attempts to resolve this contextual disconnect range from instructional frameworks [94], to social media integration [43], to physical laboratory work as it provides a connection between the class material and “the real world” [36]. When used properly, lab work improves overall learning outcomes [98], positively effects student engagement [6], and contextualizes the material [115]. Yet there are challenges to

overcome with implementing physical lab work, including safety and cost, that point to educational technologies as a solution.

A common solution is virtual simulations designed to mimic the experience of physical lab work [93]. An extensive review by Brinson suggests that non-traditional labs, such as virtual and remote implementations, are as effective as traditionally implemented physical labs [15]. Even partial emulations of physical lab experiences are shown to have positive effects on the learning process. For example, Herga used animations and dynamic simulations of chemistry models to positively impact students' formation of mental models [40]. Monitor-based educational technologies often provide virtual laboratory simulations, where certain parts of the physical lab experience are emulated digitally to help achieve a specific learning goal. Some examples are labSimuLab, ChemVLab+, MatLab simulations, and Multimodal Virtual Chemistry Laboratory.

ChemVLab+ is a monitor-based application that allows students to solve real-world lab problems [23]. Designers of ChemVLab+ focused on integrating science practices into an authentic context while providing immediate feedback with simulated measuring tools. labSimuLab is a monitor-based learning tool where certain lab processes are accelerated to allow more time for interpretation of results by students [49]. Al-Moameri studied an approach of using MatLab simulations as a core around which the textbook was designed. Using MatLab for the simulations was proven to be a practical solution given its availability and ease of integrating computing with visualizations [3]. Multimodal Virtual Chemistry Laboratory is a multimodal simulation experience designed for easy procedure guidance where students can get feedback on their chemical mixing procedure from either textual or tactile modes of interaction [114]. Beyond monitor-based implementations of laboratory simulations, AR/VR technologies have begun to be explored for their potential to emulate the laboratory experience.

Akcayir demonstrated a physics laboratory augmented reality (AR) experience, and showed it was effective in increasing laboratory skills, improved students' work speed, and allowed for more discussion time [1]. Yee demonstrated a chemistry AR educational technology for colorimetric titration, which proved to be effective while remaining cost-efficient [111]. These results align with existing literature as confirmed by Cheng and Tsai, whom compiled a literature review of AR educational technologies for STEM lab work, classifying them into image and location-based AR [20]. Image-based AR delivers affordances including spatial ability, practical laboratory skills, and conceptual understanding. Location-based AR provides opportunities for supporting inquiry-based learning using collaborative role-play gaming [20]. In one study, Barrett described VR as providing a more tactile experience, where he implemented a VR table as a collaborative educational technology tool for undergraduate laboratory sessions [6]. While the body of research for AR virtual laboratories was relatively substantial, little was found for VR virtual laboratories and further studies will be required to identify the impact of such technologies.

The studies reviewed in this section have revealed a large body of work supporting the effectiveness of physical laboratory work as a tool for learning in STEM education. In addition, it is shown that educational technology from monitor-based to AR/VR implementations can virtualize aspects of physical laboratory work and still maintain the lab's effectiveness as a STEM learning tool. While AR/VR educational technologies are not reviewed heavily, the current generation of monitor-based educational technologies has been and suggests that virtualizing physical laboratory work may be a prime supporting capacity for future AR/VR education technologies in the STEM fields.

2.6 Educational Technology Contextualizes STEM Education

The previous section showed that principles of constructivism can be applied effectively in the context of physical lab work for STEM education, and that virtualization of lab work can provide benefits over its physical implementation. When designed correctly, educational technology and hands-on programs can create active learning scenarios in STEM education to promote students' learning and engagement factors. A study conducted by Christensen et al. examined positive STEM dispositions of students from three different programs using the STEM Semantics Survey [21]. They concluded that active learning programs can improve or maintain STEM dispositions in high school settings [21]. CS education curriculum revolving around making animations or games have proven to be successful in primary students, resulting in increased student engagement [120]. Game-based learning in after-school programs, such as Lee's work using the Gidget programming game, has shown to increase learners' engagement in with programming, even for members from underrepresented groups in computing [63, 62, 66]. Engaging students with interactive visualizations and simulations can be a powerful supplemental learning tool that AR/VR may be able to enhance.

Pancratz and Diethelm focused on the students' thought process to help underrepresented STEM minorities, such as females, to improve their enrollment and retention in a CS degree [88]. They demonstrated that teaching problem solving techniques by breaking down large problems into parts not only teaches good life skills but helps a larger student audience learn fundamental CS concepts, such as object oriented programming, modularity, and divide and conquer techniques. The research team used rapid prototyping techniques for small Internet-of-Things as the teaching medium, and showed that having students focus on small hands-on projects helps them learn fundamental CS concepts. Zhu and Panorkou looked at the whole of simulation technologies to help students comprehend STEM concepts [128]. They

explored use cases of computer simulations in K-12 environment science involving the modeling environment, Netlogo, and the visual programming language, Scratch. Students were able to manipulate system parameters and interpret the results of environmental changes. The presented studies demonstrated novel approaches to teaching complex CS and STEM concepts using computer simulations whose effects may be enhanced using AR/VR technologies.

Other researchers have also looked at a similar challenge of inspiring non-STEM students to become interested in STEM and CS learning using immersive technologies [103, 106, 108, 118]. Wang and Frye used VR to focus on engaging art aspects of STEAM with experiential learning to recruit underrepresented females into STEM [118]. Surveys indicated that students had minimal STEM backgrounds and found the arts and crafts style hands-on activities were engaging and helped them acclimate to abstract concepts and STEM career potentials. Seo and Lawrence exposed design students, especially females, to software engineering with VR as an approachable technology [103]. They used design focused students inherent interest in visual technologies to teach them that CS concepts are an approachable academic discipline. 3D printing, CAD software, and VR technologies were a variety of teaching aids used in this project-driven workshop. The researchers showed the importance of visualizing STEM topics when teaching them to non-STEM students, which instructed the visual design of the prototypes be as literal as possible for students to make the visual connection to the material presented to them.

Shamir et al. taught and increased interest in CS to non-CS students with VR, art, and animation [106]. They developed a teaching paradigm using interlacing structures in dancing, body poses, song melodies, and painting composition that increased student interest in pursuing VR careers. They showed that incorporating physical activities and creative pursuits with CS education can increase student engagement, and resulted in designing the prototypes' educational experiences with

physical movements and creative decisions in mind. Frydenberg and Andone found that having students collaborate on VR projects increased their interest in technology [29]. The project paired students from universities in the United States and Romania to remotely visit and learn about each other's region and culture through shared VR development projects. Students reported broadening their understanding of applications for future technologies. Using emerging technologies can increase integration of STEM education and demonstrates new directions for virtual learning environments. AR/VR learning environments can promote discussion of ideas between learners with enhanced spatial and visual explanations of abstract topics supported by user environmental exploration and interactions that are not easily reproduced in physical environments.

2.7 Conclusion

Learning science theories indicate the importance of constructivist cognition in the learning process. That active learning scenarios, with physical attributes, often offer the best learning performances. These ideas of embodiment offering better learning experiences appear across the learning and HCI sciences. In fact, the review of existing literature identified many benefits to using educational technologies in STEM education. Educational technology provides ample opportunity for constructivist cognition in the form of active learning. Additionally, the immersive qualities of AR/VR educational technology can help contextualize STEM topics to students.

The studies presented in this chapter discuss the benefits of physical lab work and technology usage in contextualizing STEM education. This contextualization of abstract material has shown demonstrated improvements in learning performance. The studies showed strong evidence that the embodied qualities of physical laboratory work helps contextualize STEM education, and that physical laboratory work can be effectively virtualized with educational technology to maintain the same learning

benefits while removing the physical constraints of space, location, cost, equipment, and personnel.

Although these studies point to both the benefits of physicality to aid constructionist learning in STEM education, and the benefits of virtualizing the physical learning environment, learning science and HCI user studies were hard to find specifying the type and details for physical user actions associated with cognition that aid with the learning process. The studies in the literature review indicate that virtualizing physical laboratories are an effective teaching technique, but are there differences between a non-traversable and a traversable virtual learning environment? If so, how do each compare to a physical learning environment? And if principles of embodiment can impact the learning experience, what parts of the body and types of body movement might impact learning performance?

To address this gap in research, this dissertation examines the impact of one virtual environmental factor, traversal fidelity, on the efficacy of immersive virtual learning environments. The first of three studies compares the effectiveness of AR/VR educational technology against live instruction without traversal of the virtual learning environment, while the second study does the same comparison with traversal of the virtual learning environment, and the final study seeks to isolate the effects of traversal fidelity as an environmental factor for immersive virtual learning environments. It is the intention of this dissertation to increase the knowledge of the learning and HCI sciences to help identify how physical user actions associated with cognition can aid with the learning process.

CHAPTER 3

EFFECT OF NON-TRAVERSABLE IMMERSIVE VIRTUAL ENVIRONMENT ON LEARNING IN STEM EDUCATION

3.1 Introduction

In today's educational environment, increasing demands require educators to use new techniques to improve the quality and frequency of learning experiences [87]. learning community (LC)s are one well-researched approach to using structured socialization environments to maximize the potential for informal learning opportunities [9]. Higher educational institutions often formalize LC skill training for their incoming undergraduate student population with regulated fall semester classes called freshman year seminars (FYS), which traditionally takes the form of physical (i.e., in-person), classroom-based environments. Recent studies have shown that virtual LC environments can offer improved results over physical LC environments [50].

This chapter examines whether STEM learners gain the same benefits to their academic performance regardless of whether they receive collaboration training in physical or virtual treatment. It explores the effects of a non-traversable immersive virtual environment on undergraduate STEM students learning collaboration skills, which are important for learners entering a new professional environment where the social support network can be vital to their survival. Collaboration training is a suitable medium to compare virtual and physical treatments without the environmental traversal variable as most collaborations involve individuals working in a LC in a stationary manner.

This chapter presents the first of three studies examining how traversability in virtual learning environments impacts user performance. It compares the efficacy of a non-traversable virtual learning environment against live instruction in a physical learning environment. The research questions are:

1. How does a non-traversable AR/VR environment impact learner performance?
 - (a) Is non-traversable AR/VR environment as effective as in-person instruction?
 - (b) How does a non-traversable AR/VR environment impact user perceptions?

3.2 Related Work

A LC is a group of people who share common academic goals and attitudes; who meet semi-regularly to collaborate on classwork [9]. These groups are documented to provide a significant positive impact on participating students' academic performance [34]. Carrino and Gerace found that socialization factors such as collaboration, networking, and organizational thinking are of particular interest due to their critical influence on students' ability to form LCs independently. These skill sets are important for STEM students that statistically spend less time honing these social skill sets [18], which STEM careers value highly.

LCs vary depending on desired outcomes and do not have a definitive set of implementation guidelines. The literature does, however, provide best practices and theoretical frameworks to inform LC education [37, 127]. Implementing appropriate scaffolds and curricular structures are also considered a good practice [112]. The benefits of LCs and other programs targeting first-year students extend beyond academic improvements. Improved engagement with peers and instructors has a positive impact on overall engagement [57]. In more recent literature, Settle demonstrated that participating in LCs showed increased retention rates [105] and improved on feelings of isolation [104] in minority student cohorts.

LC curriculum needs to address skill training at the individual and social level to be successful in STEM education. Carrino and Gerace analysed two years of open-end response questionnaires and interviews from participants in STEM based LCs. Their codification process revealed two primary categories of positive effects on participants: the individual and social level. The individual level had codes involving self-efficacy,

self-regulation, identity and meta-cognition. The social level has interaction with faculty/professionals and with peers. Their research confirmed the individual and social aspects of learning science have a strong impact on LC curriculum, and that the growth of self identity and efficacy area are necessary to enable better socialization and collaboration with STEM professionals and peers alike.

These individual and social categories of learner growth are important to consider when developing LC curriculum, structure, and assessments, as well as alternative curriculum deliverable methods. Boyce and Mishra found evidence that virtualizing LCs has the potential to expand and supplement existing learning structures, and create new ones where not previously available [14]. They conducted educational research deploying tablet computers outside the classroom to direct informal LC assignments in environmental science primary education. The researchers used qualitative data collection techniques such as ethnographic observation, surveys, and interviews to understand the impact to the students. It was found that technology usage, e.g., a virtualization of the LC curriculum, improved student engagement with the STEM topics, student socialization, and attitudes toward nature.

Both physical and virtual LC structures need to be sympathetic to the quality of instructors and students interaction to ensure high retention for STEM learners. Guidelines proposed by Yuan suggest using both synchronous and asynchronous technologies to overcome issues with presence and schedule, which are not limited to online students [126]. Yuan identified instructor quality and interaction between learners as factors for dropout rates in STEM programs. Online LCs are also useful in reducing the negative impact of limited communication of students in online classes.

Virtualizing LC has the potential to expand and supplement existing learning structures, and create new ones where not previously available [14]. Virtualization can improve learning interaction and overcome instructor quality variation if implemented successfully [14]. Guidelines include continued and iterative curriculum development

through the lifetime of the program, consistent feedback from both learners and instructors incorporated regularly, use of synchronous technologies to create a shared virtual learning space, varied and flexible approaches to consistently stimulate discussions amongst learners, encouragement of both task-oriented and socialization group discussions, and assignments centered around collaboration activities. This research will lead to a better understanding of the strengths and limitations of introducing AR/VR technologies in higher education for collaboration training.

3.3 Method

3.3.1 Study Design

The study was a between-group design with three groups: control, physical treatment, and virtual treatment (see Table 3.1). All participants were placed randomly into the control and treatment groups. The control group had no LC training, the physical treatment group had LC training in a physical environment, and the virtual treatment group had LC training in a virtual environment. The two treatment groups were randomized again when they were divided into smaller teams for effective LC training. Curriculum topics, activities and weekly structure were developed with the FYS director.

Table 3.1 Treatment Group Details

Group	Subjects	Collab	Assessments
Control	28	None	Academic/Social/Survey
Physical Treatment	29	Physical	Academic/Social/Survey/Interview
Virtual Treatment	33	Virtual	Academic/Social/Survey/Interview

The null hypothesis of the experiment was that there was no measurable differences of the academic and social metrics between any of the control and

treatment groups. The alternative hypothesis of the experiment was that there was measurable differences of the academic and social metrics between the control and either (or both) of the treatments groups.

The independent variables in the experiment were whether a participant had LC training, and whether that training was administered in a physical or virtual environment. The dependent variables were the participants' self-reported academic grades from their common core exams, weekly self-reported peer socializing, and perceptions on collaboration as formed from the environmental variable for the collaboration training. The essential dependent variables were the academic and social metrics which were gathered as quantitative data. The exploratory dependent variables were the participants' perceptions on collaboration, which were gathered as qualitative data to complement and better understand the quantitative results.

New curriculum was developed to test between two experimental conditions (physical in-person interactions vs. virtual interactions using the exact same curriculum), and a control condition (the current LC instruction at New Jersey Institute of Technology (NJIT) using their original curriculum). Specifically, we compared the following outcomes: academic performance, and social connectedness.

The experimental groups had learning sessions regularly at the same time, with the same instructor, and same the frequency as FYS sessions for eight weeks. Academic and social assessments were administered to participants during and after treatment for the entire semester over 15 weeks. Qualitative measures of participant preferences and opinions of the collaboration training were gathered from semi-structured interviews.

3.3.2 System

The virtual treatment used a networked, multi-player social VR software called "Facebook Spaces" made by Facebook [85]. It allows up to four users to connect



Figure 3.1 Screenshot of virtual treatment participants in “Facebook Spaces”.

remotely via Facebook accounts to a virtual space. The space includes a flat 360 panoramic image for the surrounding environment, and a circular table for up to four users to sit around to interact with each other, objects and the environment. The feature set available within the Facebook Spaces software, includes discussions, drawing, dice, playing cards, 3D model viewing, and photo viewing (see Figure 3.1).

3.3.3 Stimuli

Each user in the virtual treatment was represented by a virtual avatar that was placed in a stationary position around a circular table, see Figure 3.1. The avatar’s head was moved by the user’s head rotations with a head mounted device. The avatar’s hands were moved by the user’s hand positions and rotations through inverse kinematics with hand controller devices. The user saw the virtual space through the head mounted device. The user could speak through a microphone and listen through headphones in the head mounted device. Finally, the user could interact with objects in the space with the hand controllers.

3.3.4 Participants

Each fall semester, NJIT offers 55 LC class sections and 5 non-LC class sections to freshman undergraduate students, with approximately 25-30 students self-enrolling into each section. We visited most class sections during the first week to explain the study and recruit participants from NJIT's College of Engineering and College of Computing (representing 75% of the total student body).

To account for instructor effects, the participants were randomized into each group. Each experimental group had 8 teams of 3-4 participants each, for a total of 62 participants. The control group had no teams as they only had to fill out assessments for the study, and included a total of 28 participants. We compensated each participant a minimum of \$150 for the duration of the study, requiring them to participate in the study for 2 hours each Wednesday, for 10 consecutive Wednesdays (equating to \$15/hour, which is 107% more than the federal minimum wage of \$7.25, and 74.4% more than our state's minimum wage of \$8.60).

3.3.5 Procedure

For the control group, participants had their FYS curriculum as-is with no additional LC training. For the physical treatment, participants were randomly placed in groups of four as that was the size limit for the virtual treatment. The physical treatment groups met in a small meeting room at a table and were guided on physical group activities. For the virtual treatment, participants were randomly placed in groups of four and used the social VR software, Facebook Spaces. For each virtual treatment session, the participants were separated physically, connected together by networked computers around a virtual table and were guided on the virtualized group activities. During the initial stages of the study, the virtual treatment participants came for assistance and training to interact within the virtual space using the hardware controllers and software.

Implementation began with an exploration and design phase for the virtual and physical collaboration curriculum modules. A corpus of unique curricula was created spanning several socialization and collaboration topics oriented toward learning community skill sets (explained further in the following subsections). The collaboration curriculum was aligned so both the physical and virtual form would be equivalent. Both curricula was structured around the feature set available within the Facebook Spaces software, which included discussions, drawing, dice, playing cards, 3D model viewing, photo viewing around a round table. Facebook spaces allows a maximum of four participants in a session, so all of the study's groups were limited to 3-4 participants each.

The experiment ran for the first eight weeks of the semester to coincide with the FYS classes. Assessments ran for the entire semester to measure the full academic and social impact of the LC training. Academic assessments were self-reported by the participants at the four common core and final exams that all first-year students must take in their required math and science classes to acquire as much academic data possible. Social assessments were based off established Social Network Analysis and were self-reported in weekly intervals to maximize the chances that the participants would remember their social interactions with peers from their classes. Participants in the two treatment groups were interviewed at the end of the semester to give them as much time as possible to see how the LC training impacted their academic and social performance during their first semester at college.

Collaboration Curriculum The study ran concurrent to the FYS classes, which were active for the first ten weeks of the fall semester. The two treatment groups, physical and virtual, went through eight weeks of the collaboration curriculum (see Table 3.2), which included the same activity between the two treatments for one hour each week. We outline these activities below:

Table 3.2 Weekly Collaboration Curriculum Breakdown

Time	Physical Treatment	Virtual Treatment
Week 1	Lost at Sea	Intro to Virtual Reality
Week 2	Academic Discussions	Lost at Sea
Week 3	Ship of Theseus	Academic Discussions
Week 4	Is Hotdog a Sandwich?	Ship of Theseus
Week 5	Missionaries and Cannibals	Is Hotdog a Sandwich?
Week 6	Rocket Ship	Missionaries and Cannibals
Week 7	Moon Landing	Rocket Ship
Week 8	Pictionary	Moon Landing

Lost at Sea The goal of this activity was to introduce participants to the type of tasks they would be doing throughout the study. Each participant was asked to rank a list of items given a survival situation. The participants then discussed among the entire group to establish a group rating. In most cases, the group rating score was higher than individuals' ratings, demonstrating that group work often yields better results. The measures of success for this activity included: every member actively participated, participants understood that working in groups can yield better results, and participants responded generally positively to the activity [54].

Academic Discussions The goal of this activity was to encourage participants to share relevant experiences in the academic domain. Participants answered a list of questions regarding their study habits. The designated organizer led a discussion based on a script of questions, including "What is your favorite class so far?," "What is the class you think will require most work?," and "Do you think study groups are effective for classes?". The measures of success for this activity included: apparent

comfort of the group, attitude towards the activity, and willingness to collaborate beyond the activity.

Ship of Theseus The goal of this activity was to facilitate discussion of an abstract problem. The participants discuss a thought experiment questioning an identity of an object, called “the Ship of Theseus” thought experiment. Over time, the ship has every part replaced with a new part, and the old parts are used to build another ship. The participants are asked to discuss within their group which is the real ship. The measures of success for this activity included: participants come to some conclusions even if they do not reach a consensus [92].

Is a Hot Dog a Sandwich? The goal of this activity was to facilitate discussion of an abstract problem. The participants discuss a thought experiment questioning an identify of an object. They go through a list of foods that are questionable whether they should be classified as a sandwich, and the group must come to a discussion on each object. The measures of success for this activity included: participants come to some conclusions even if they do not reach a consensus.

Problem Solving Activities The goal of this activity was to facilitate solving a series of logic puzzles with defined solutions with focus on role and task division. The logic puzzles were titled “Missionaries and Cannibals” and “Rocket Ship”. They can often be solved with trial and error by keeping track of individual steps and backtracking them. The measures of success for this activity included: participants solved all problems in the time allotted [122].

Moon Landing The goal of this activity was to recognize progress already made as a group. This activity came from the same source as Lost at Sea and had the same structure to the activity. Since first week served as an icebreaker and the content of

the activity served largely secondary roles, this reiterated the general trend for groups to outperform individual scores. The measures of success for this activity included: the group recognized that working collaboratively had better overall results, and that they recognized they made progress since the first meeting [55].

Pictionary The goal of this activity was to serve as a morale boost during periods of increased stress and anxiety affecting all members of the group. In this case, midterm exams. The researcher adjusted rules to competitive or collaborative depending on group preferences and perception of flow. The measures of success for this activity included: every member participated, and group morale remains high [123].

3.3.6 Measures

Academic Assessment All participants filled out provided academic assessments in designated forms and times during the semester (see Figure A.1). Data collection points occurred in person on a one-on-one basis starting at the beginning of the semester, and ending at the end of the semester. The participants were required to fill out the academic assessment a week before all exams and final grades were due.

The academic assessment was a form asking the participant to list any classes they had an exam or grade in within the next week, and what grade they believed they would receive from A to F, which was converted to 1-5 (only integers). The participants had on average five classes and each class had between 3-4 exams along with a final class grade, resulting in a minimum of 4 grade data points.

Social Assessment All participants filled out provided social assessments in designated forms and times during the semester (see Figure B.1). Data collection points occurred in person on a one-on-one basis starting at the beginning of the semester, and ending at the end of the semester. The participants were required to fill out the social assessment every week during the semester.

No established methods were found for measuring students' connectedness in LC settings. Therefore, we adapted work from Social Network Analysis for the social metric, which is a tool for describing the underlying mechanisms for social dynamic theory. The resulting social metric was a form asking participants to list out fellow students that they had academically-related social interactions with over the past week. These "academically-related social interaction" were defined as at least five minutes of socialization, either in-person or remotely, in any location outside of the classroom where the participant was given help or gave help in regards to a class activity (e.g., an assignment). The form had room to list out five classes (the average number of classes for a freshman) and up to 12 fellow students per class with directionality (i.e., half indicated that they *provided* help to someone else, and half indicated that they *received* help from someone else).

Interviews At the end of the semester, 1-hour semi-structured interviews were conducted with participants from both the treatment groups. 26 participants were interviewed from the virtual treatment group and 19 from the physical treatment group for a total of 45 interviews. Two researchers conducted all the interviews, one for all physical treatment participants, and the other for all virtual treatment participants. A total of 23 questions were asked intended to better understand how the different treatments affected participants' opinions about collaboration and LCs. A sample of our questions include:

1. Which activity did you like the most?
2. Was there an activity you really disliked?
3. Do the activities help students communicate better?
4. Are you more likely to ask students for help?
5. Are you more likely to socialize with other students?

A three-stage coding process described by Cambell et al. was used for the measurement of intercoder reliability for semi-structured interviews [17]. The lead interviewer read through all interviews and generated a list of themes. A second researcher reviewed 10% of the transcripts and reached a minimum of 87% intercoder reliability after two trials (86% than 89%). Once this was complete, the lead interviewer coded the remaining transcripts and counted code occurrences.

After consolidation, 52 codes were identified and grouped into 10 themes. The occurrences of each code were coded as a binary output, no(0)/yes(1). As the resulting data are nominal/categorical, the counts of the different labels (e.g., histograms) were reported; shown as percentages of 'yes' responses per group.

Codes grouped into their themes:

1. Factors for choosing NJIT:
Family, Reputation, Finance, Location, Academics
2. Current experience at NJIT:
Academic, People, Independence, Campus
3. Motivations behind collaboration:
Sharing ideas, Social, Solving problems, Shared workload, Helping
4. Significance behind collaboration:
Social skills, Mindsets, Jobs, Comfort
5. General activities participants liked or disliked:
Sports, Games, Social, Academic, Difficulty, Public speaking
6. Perception of roles in collaborative activities:
Assigned, Natural, Leader, Follower, Multiple, Power, Ability, Interest
7. Mentors and their roles on collaboration:
Guidance, Per request, Supervision, Contamination

8. Collaboration activities participants liked:

Problem solving, Novelty, Competitive, Fun, Word-based, Different views

9. Purpose of LCs:

Guidance, Comfort, Getting to know people, Building relationships, Future

10. Effects of collaboration activities:

Friends, Being heard, Easier to work, Communicating, Differences

3.4 Results

3.4.1 Academic Difference between Treatments and Control

Academic assessments were gathered that were filled out throughout the semester and converted letter grades of A through F to a scale of 1 to 5. All academic assessments were averaged per participant to get a final academic metric, which was analyzed as ordinal variables using the non-parametric Mann-Whitney test (as the data was not normally distributed). No significance was found in comparing the treatment groups ($U = 954.0, n = 62, p = 0.573$), meaning there was no observable difference between the physical and virtual treatment group participants' self-reported semester grades. However, significant difference was found between the physical treatment and control ($U = 993.0, n = 57, p = 0.016$) and between the virtual treatment and control ($U = 726.5, n = 61, p = 0.041$), with both the physical and virtual treatment groups having a significantly higher self-reported semester grades (control median = 3.792, physical median = 4.0, virtual median = 4.0) (see Figure 3.2).

3.4.2 Social Assessment Difference between Virtual Treatment and Control

The social metrics of the three study groups were compared by examining the total academic social interactions per semester of each participant and the directional sums of their social interactions (giving or receiving help). Chi-Squared tests were used as the data was not normally distributed. A significant difference was found

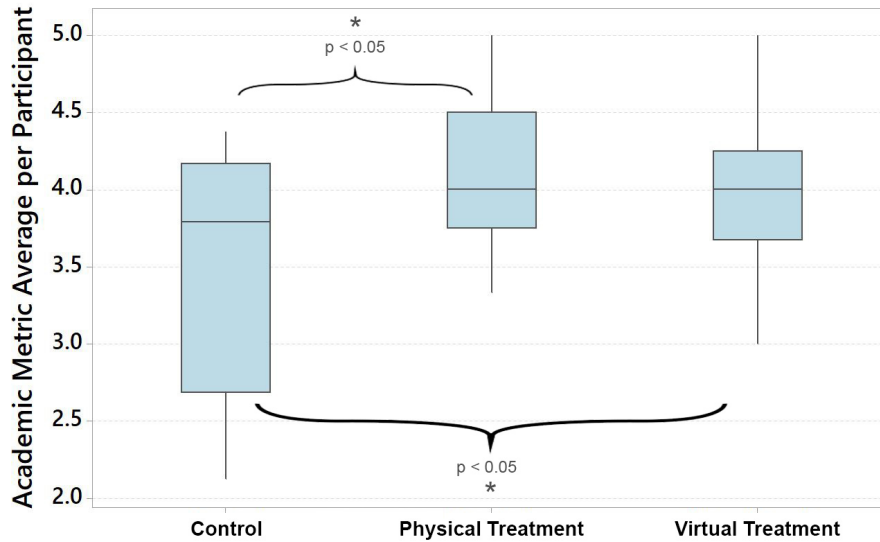


Figure 3.2 Boxplot of academic metric average per participant by study group.

when comparing virtual treatment to the control group for giving help ($\chi^2(2, n = 57) = 5.6531, z = 2.376, p = 0.0175$), with the virtual treatment participants giving significantly more help than their control counterparts (see Figure 3.3).

3.4.3 Interview Codifications of Physical and Virtual Treatments

For the *mentor roles on collaboration* theme, the *guidance* code appeared in 88% of the virtual treatment participant interviews and 32% of the physical treatment participant interviews. This means the virtual treatment participants mentioned the idea of guidance 2.75 times more than the physical treatment participants when asked about mentor roles on collaboration (see Figure 3.4).

For the *perception of collaboration roles* theme, the *natural* and *ability* codes appeared in 79% and 42% of virtual treatment participant interviews and 63% and 21% of physical treatment participant interviews. This means the virtual treatment participants mentioned the ideas of natural and ability 1.25 and 2 times more than the physical treatment participants when asked about perception of roles in collaboration. The *follower* code appeared in 58% of physical treatment participant interviews and

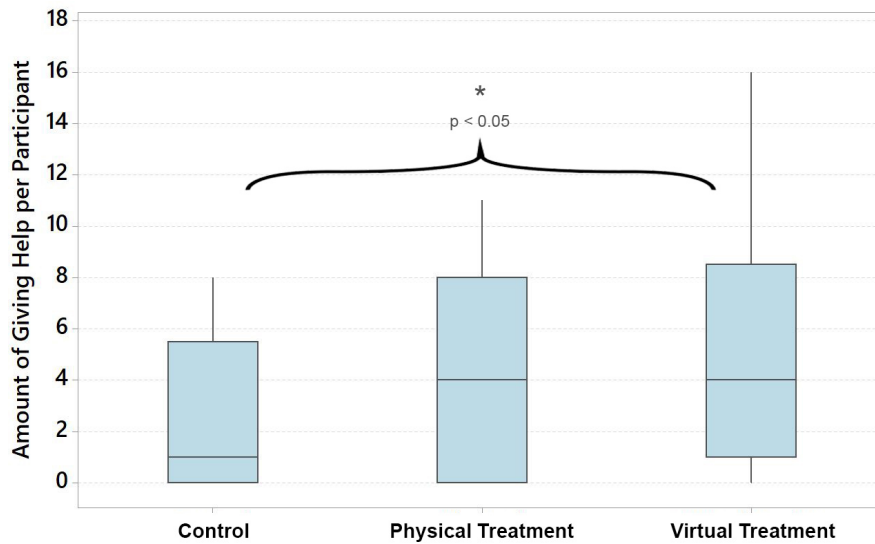


Figure 3.3 Boxplot of the social metric “Giving Help” by study group.

29% of virtual treatment participant interviews, which means the physical treatment participants mentioned being a follower two times more than the virtual treatment participants when asked about their collaboration roles (see Figure 3.4).

For the *motivations behind collaboration* theme, the *shared workload* and *helping* codes appeared in 58% and 38% of the virtual treatment participant interviews and 37% and 26% of the physical treatment participant interviews. This means the virtual treatment participants mentioned the idea of shared workload 1.57 and helping 1.46 times more than the physical treatment participants when asked about the motivation behind collaboration. The *sharing ideas* code appeared in 63% of the physical treatment participant interviews and 42% of the virtual treatment participant interviews, which means the physical treatment participants mentioned being a follower 1.5 times more than the virtual treatment participants when asked about their collaboration roles (see Figure 3.5).

For the *enjoyment factors of collaboration* theme, the *fun* and *different views* codes appeared in 68% and 32% of the physical treatment participant interviews and 54% and 17% of the virtual treatment participant interviews. This means the physical

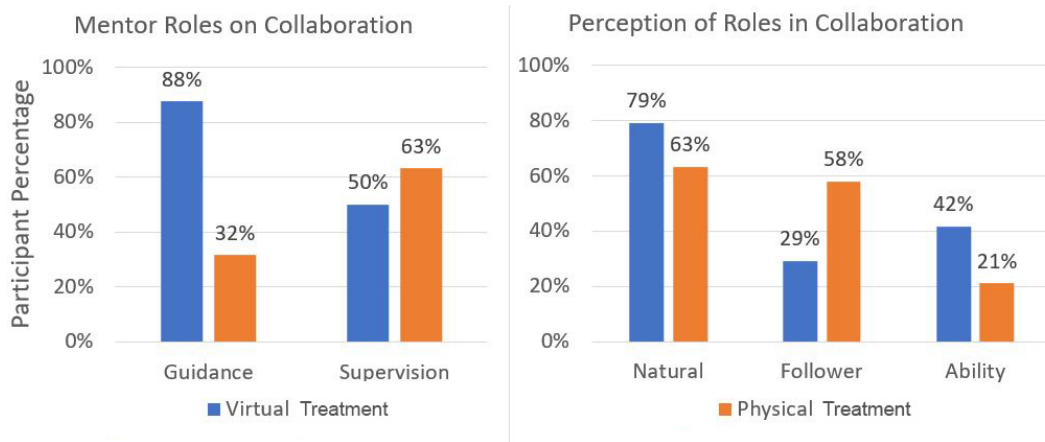


Figure 3.4 Mentor roles and perception of roles on collaboration codes.

treatment participants mentioned the idea of fun 1.26 and different views 1.88 times more than the virtual treatment participants when asked about the enjoyment factors of collaboration. The *problem solving* code appeared in 67% of the virtual treatment participant interviews and 47% of the physical treatment participant interviews, which means the virtual treatment participants mentioned solving problems 1.43 times more than the physical treatment participants when asked about their enjoyment factors of collaboration (see Figure 3.5).

For the *significance of collaboration* theme, the *jobs* code appeared in 83% of the virtual treatment participant interviews and 42% of the physical treatment participant interviews. This means the virtual treatment participants mentioned the idea of jobs 1.98 times more than the physical treatment participants when asked the significance of collaboration (see Figure 3.6).

For the *Purpose of Learning Communities (LCs)* theme, the *future* code appeared in 25% of the virtual treatment participant interviews and 0% of the physical treatment participant interviews. This means the virtual treatment participants mentioned the idea of the future 25 times more than the physical treatment participants when asked about the purpose of LCs. The *comfort* code appeared in 58% of physical treatment participant interviews and 33% of virtual treatment

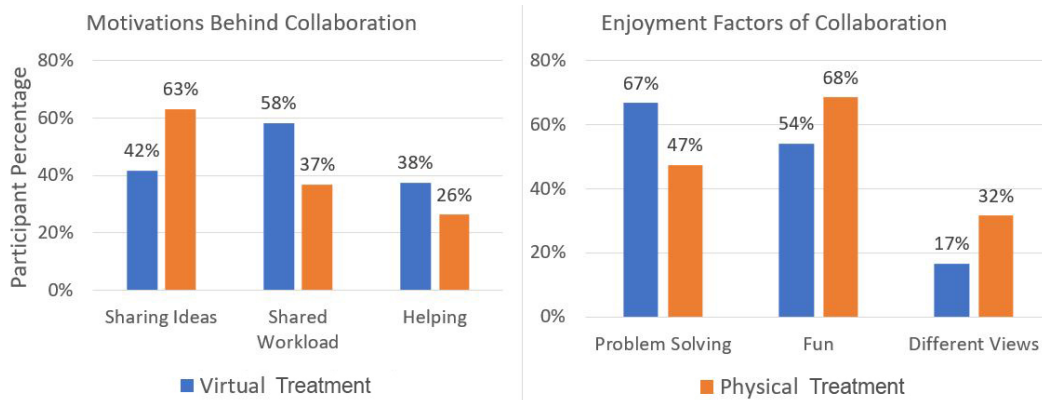


Figure 3.5 Motivations and enjoyment factors of collaboration codes.

participant interviews, which means the physical treatment participants mentioned being comfortable 1.76 times more than the virtual treatment participants when asked about the purpose of LCs (see Figure 3.6).

3.5 Discussion

3.5.1 Interpretation of Academic Assessment Difference

Analysis of the academic metrics revealed a statistical significance of the self-reported semester grades for the two treatment groups compared to the control group. It is believed that having any type of collaboration training has direct positive impact to the incoming undergraduate STEM students' academic performance. Since both the physical and virtual treatment groups had statistical academic improvements over the control group, it has been shown that virtualization of collaboration training for FYS LCs is a viable alternative to the traditional, physical training.

3.5.2 Interpretation of Social Assessment Difference

Social metric analysis revealed a statistical significance between the virtual treatment and control for the amount of academic help offered by the participant to fellow students during the semester. It is believed that this result is explained by the interview results from the motivations behind the collaboration theme. The *shared*

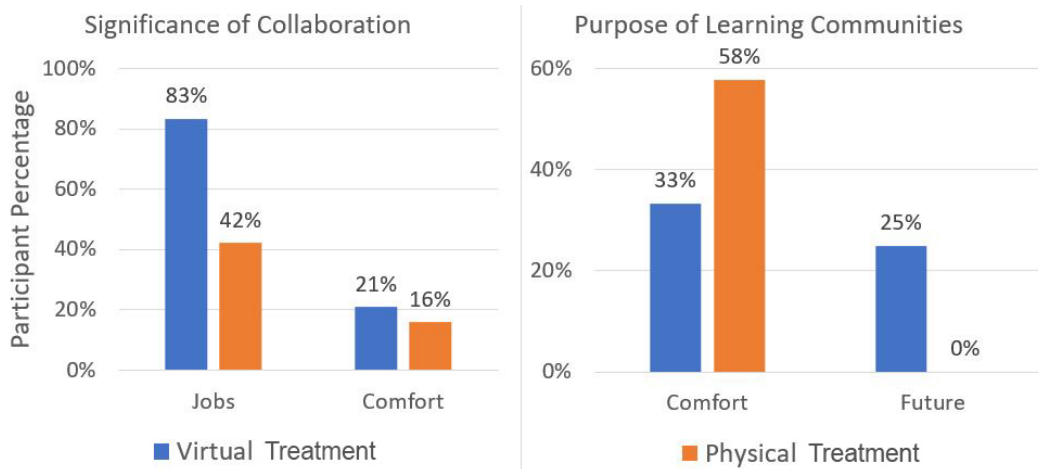


Figure 3.6 Significance and purpose of collaboration codes.

workload and the *helping* code were much higher in the virtual treatment participant interviews, showing that the virtual treatment participants learned more about offering help and sharing work, which was reflected in their giving help social metric.

3.5.3 Interpretation of Interview Codification

For the *mentor roles on collaboration* theme, the *guidance* code was much higher in the virtual treatment participant interviews. This could be a result of the large amounts of technical help and training that was needed in the first few weeks to get the virtual treatment participants acclimated to the hardware.

For the *perception of participant roles in collaboration* theme, the *natural* and *ability* codes were higher in the virtual treatment participant interviews. The *guidance* code from the previous theme may be an influential factor since the guidance during the early stages of the study may have felt as a natural ability formation for the virtual treatment group. This effect may also be seen in the higher *follower* code for the participants in the physical treatment group, which could also be interpreted in the lower follower code for the participants in the virtual treatment group.

For the motivations behind the *collaboration* theme, the *shared workload* code was higher in the virtual treatment participant interviews, while the *sharing of ideas*

code was higher in the physical treatment participant interviews. This contrast in identification of collaboration motivation between the treatment is reinforced with the additional code of *helping* being higher in the virtual treatment participant interviews. Since participants in the virtual treatment viewed collaboration motivation involving a shared work experience, it is believed they were less shy about asking a fellow group member to do a task for them. This interpretation is reinforced with the difference in the helping code between treatment. Meanwhile, the physical treatment participants had real interactions building appreciation for personal qualities such as what others were thinking and their ideas.

For the *enjoyment factors of collaboration* theme, the *problem solving* code was higher in the virtual treatment participants interviews, while the physical treatment participants interviews had higher mentions of the *fun* and *different views* codes. This preference for problem solving and different views reinforces the interpretation of the different presence of the shared ideas and shared workloads codes.

For the *significance of collaboration* theme, the *jobs* code was higher in the virtual treatment participants interviews. This may be because VR is an emerging technology, and the introduction to the VR software was set in a fictional world. These may have caused the virtual treatment participants to start thinking about their futures since many were engineering students. This interpretation is reinforced by the fact that the *future* code was much higher in the virtual treatment participants interviews from the purpose of LCs theme. It is also noted that the comfort code was higher in the physical treatment participants interviews for this theme. This would indicate that the physical treatment participants got more comfortable with collaboration which reinforcing the interpretation from the shared ideas, and different views codes.

3.5.4 Lessons Learned

Virtual Treatment Impact on Socialization Abilities The virtual treatment participants reported that VR can address the anxiety of freshman relating to their new college environment full of strangers that may carry risk of public humiliation. The virtual treatment participants indicated that socializing in VR helped remove the fear from public interactions with unknown fellow students. They reported that over the several weeks of the study, they felt more comfortable during the rest of their week when they were out on the campus and interacting with other students.

Preference of Cooperative vs Competitive Activities The study focused mostly on collaborative problem solving but games worked well and were usually successful in groups with past poor performance. Most groups direct their interactions around cooperation, or at least a mixture of cooperative and competitive with the competitive interactions blending into a cooperation nature, and vice versa. One group would only compete with each other and another group had very low interactions in general, but leaned toward cooperation interactions.

Open-ended vs Concrete Solutions The treatment participants seemed split on open-ended vs closed solution problems. Some participants pointed out that problems with defined solutions are more satisfying to solve, with the solution serving as a kind of reward. Participants that preferred the Ship of Theseus and “Is a hot dog a sandwich?” type problems, listed a variety of causes, including:

1. Open-ended problems are more challenging
2. They liked the opportunity to discuss and debate
3. These kinds of problems are different
4. Longer problems have depth to talk about

Additionally, some of the participants are inclined to lead and moderate and this could affect their preferences.

Session Breakdown The researchers found it useful to observe the group as they entered the room, and trying to start with activities that are at the group's emotional state and allow them to warm up. At the beginning, the researchers stuck mostly to a single activity per session. The fourth week started a slow introduction of other activities, like card games, and the week 5 activity was three different problems presented as a single activity. Some participants liked the variety of having multiple activities, others preferred to focus on one.

Math Anxiety Breaks Collaboration The counting task involving math could stop collaboration as participants were afraid of making a mistake and being embarrassed in front of their group. In the future, it will be best to avoid activities that break the flow of collaboration and discussion as it simply defeats the purpose of our intervention.

Three Types of Group Mentalities: Talkers, Doers, Not Ripe Yet The "Talker" groups preferring discussion activities, their interactions peaked around conversations. Conversations were not all collaborative, they flow between collaboration and competitive natures with the main dialogue themes exploring personal opinions on a subject. After personal explorations, they can easily come to group decisions. Usually, these groups were formed around one personality with the others feeling comfortable as a secondary personality with followup comments or confirmation or reject of direction that the group leader is going. Usually, these roles were define based on the communication abilities of each member, with the last group member having the lowest socialization ability listening, and doing something with their hands, i.e., drawing or playing with models, but still verbally confirming their

approval of the group's direction. It is currently unknown if these groups only form when there is this single dominant personality.

These groups enjoyed all collaboration activities with personal preferences ranging on the types of activities. They usually do not need to be warmed up, or coerced into interacting with each other, and usually were very excited to start up their session and bonded quickly as a group. They came in together chatting, were quick with the assessments, and any logistics of the study since they help each other, and left the sessions together. This phenomena made the researchers curious about using another assessment of checking their times to coming into the study, the speed of filling of the assessments, speed of entering into VR, and speed of finishing up activities.

The "Doer" groups preferring physical activities, their interactions peaked around games, puzzles, activities that can be completed successfully with minimal conversations and more interactions involving physical manipulations with the hands. Tactile stimulation and manipulation was preferred for shared experiences. It is not known if this is because the group did not have a persona to lead the conversation situations and they preferred these more silent group activities. It may have be a hierarchy situation based on the social skill level of participants, and that all participants matured through these levels of preferred group dynamics and social interactions. For this study's purpose, the researchers were trying to get the participants to be as comfortable conversationally as possible since the end goal is to maximize the chances that out in the real world of campus and class interactions they would ask for help when needed and offer help when capable to do so.

This style of group dynamic seemed to prefer logic puzzle activities when forced to do a conversational activity. This seemed to be because they can rely on a tactile interaction point with the group, i.e., drawing, to supplement their conversations when interacting with each other to solve the puzzle. These groups seemed to prefer

collaborative tactile exercises like Pictionary and puzzle-solving as that seemed to avoid confrontations. They seemed to want to positively interact with the group but lacked the confidence or experiences to do so in full conversational situations.

Only two groups were “Not Ripe Yet” and not ready for any structured type of interactions. They needed unstructured playtime to pull out group interactions, and exploratory environments with opportunities for immature jokes. The simplest games of hangman and blackjack were most effective. Their collaboration fell apart under conversations and goal-oriented activities. Although both groups solved the missionaries puzzle, which was surprising, they did poorly compared to the other groups. The logic puzzle gave them something interesting to solve where they did not need to perform in front of the rest of the group. Pictionary did not work well because they were focused on making fun of each other’s drawing skills which gave them performance anxiety for both the drawer and the guesser.

They needed activities with minimal structure. The researchers gave them 3D models to play around with to get used to the presence of the other participants. That was followed up with some type of activity that gives a small amount of structure and performance but not enough to evoke sarcasm from the group and elicit performance anxiety. After that, the session was usually followed with a mildly structured activity when it was needed to actively promote positive collaboration experiences while minimizing the potential for public humiliation. Of the two groups with this mentality, both were all males, with one all Caucasian and the other all African-American. Most girls in the study were more socially advanced, more collaboration and conversation focused, yet did seem shier and tended to not be the primary personality of conversation groups. It is thought that had mostly to do with the fact that they are an underrepresented minority.

3.5.5 Study Limitations

The development of the collaborative activities was limited due to the study's requirement of keeping everything consistent across conditions. The software used in the virtual treatment had limited tools for user interactions, so the activities were built around these limitations.

3.6 Conclusion

This chapter compared the efficacy of a non-traversable immersive virtual learning environment against live instruction in a physical learning environment. The effects of the treatments were examined upon a population of incoming undergraduate STEM freshmen students learning collaboration skills, which are important as modern educational and work environments are highly team-centric. Collaboration training is a suitable medium to compare virtual and physical treatments without the environmental traversal variable as most collaborations involve individuals working together in a stationary manner.

Either treatment of collaboration training was found to improve the participants' academic performance in comparison to the control treatment. This evidence suggests that instructional delivery in a virtual environment with no traversal of the spatial AR/VR interface offers comparable learning efficacy to the traditional physical environment. In addition, the virtual treatment participants gave more academic help in social settings to their peers throughout the semester than their control group counterparts. Upon interviewing the two treatment group participants, the virtualization of collaboration was found to positively impact perceptions on leadership roles, group functions, and thinking about their future careers.

CHAPTER 4

EFFECT OF TRAVERSABLE IMMERSIVE VIRTUAL ENVIRONMENT ON LEARNING IN STEM EDUCATION

4.1 Introduction

Educational fields may find alternative teaching methods useful to maximize student opportunities to internalize and process the curriculum. AR/VR educational experiences have the potential to be used as alternative teaching tools in STEM education, which can supplement traditional teaching methods enabling new learning methods for students in the classroom and at home. This chapter examines whether STEM learners can gain the same academic performance benefits regardless of receiving CS training in physical or virtual modalities. It explores the effects of a traversable immersive virtual environment on middle school students learning binary (base-2) counting, which is an important computational skill for CS learners. The outcomes from this research can support a larger effort in adapting the current STEM education system to meet the needs of a more diverse student body that may find alternative teaching tools useful in internalizing abstract concepts.

The goal of this chapter is to examine if a traversable AR/VR educational experience could have the same benefits as live lecture in the classroom for student understanding binary (base-2) counting. To address this goal, a controlled experiment was conducted comparing a teacher-led lecture (the control) and a AR/VR experience (the treatment) introducing binary counting. AR/VR technology was designed with the teacher and student considerations in mind, as a CS educational technology in school settings. When designing AR/VR educational technology, having the user move through and interact with the virtual environment may help learners engage with abstract STEM concepts and attract a more diverse population to CS and STEM. With this objective in mind, a CS educational VR experience, called CSpresso,

was developed to teach students to count in a binary number system. The study compared the efficacy of a traversable immersive virtual learning environment against live instruction in a physical learning environment. The research questions were:

- How does a traversable AR/VR environment impact learner performance?
 1. Is a traversable AR/VR environment as effective as in-person instruction?
 2. How does a traversable AR/VR learning environment impact usability?

4.2 Related Work

The traditional method of CS teaching involves lecture and textbook methods, with alternative teaching methods involving project-based learning and interactive programming tools. Modernizing education practices with interactive technology to supplement traditional teaching methods may give students additional opportunities, at school and at home, to be given the opportunity to excel in the field [117]. However, technology usage in the classroom often depends on the teacher's beliefs and their teaching philosophy [27, 117]. Instructors' self-efficacy is one of the most significant factors that impact their use of technology in the classroom [27]. Participatory design initiatives allow instructors to familiarize themselves with the technology allowing them to suggest modifications, which can help align the technology with their pedagogical beliefs better.

This gives educational technologists an opportunity to increase the positive impact of technology in the classroom. They can increase the overall usage of such technology if they consider integration in their design. The newest generation of AR/VR headsets, called standalone VR, have wireless free roaming features that may be able to accomplish an engaging virtual learning environment that is a self-contained alternative teaching tool in the classroom and at home [85]. Based on this hypothesis, an educational VR experience was co-designed, *CSpresso*, with CS educators, to be accessible, engaging with its narrative and gameplay, and have an adjustable pace

to match an individual's learning pace [107]. The aim was to use AR/VR as an alternative teaching tool to attract a more diverse student population who may not otherwise choose to learn CS.

Game-based learning is an approach to education that uses games to enhance or facilitate the learning process, which encompasses VR. Unlike gamification, this approach does not limit itself to using game mechanics such as incentive systems in non-game settings [2]. The exact relationship between game complexity and learning has not been definitively confirmed by literature [95]. The effectiveness of games used purely as a substitute for “drill and practice” activities has not been verified by existing research [110] as well.

Among the frequently cited reasons for the use of games are motivation and engagement that games enhance in their players [91]. The impact on skill and knowledge acquisition is the common measure of success in games in education settings [22, 95]. Recent reviews by Qian et al. suggest an expansion of criteria to include problem-solving and other skills, sometimes referred to as “21st-century skills” [95]. They highlight recent interest in approaches expanded beyond course material and educational outcome measures, such as computational thinking and problem solving skill building.

Studies examining the impact of game-based learning approaches in mathematics have shown improvement in self-efficacy and increased learning motivation in addition to improved learning achievement [42]. Applications that depend on game-based learning to encourage students to self-study have also shown a positive impact on math scores [19]. To better understand different student populations, Ku et al. investigated the effect of game-based learning on confidence and performance by separating participants into low and high ability groups for math education [59]. Ku et al. compared traditional paper-based instruction in a physical environment to a digital game-based instruction in a virtual environment. While students in both groups

improved in performance, the low-ability students have shown improved confidence in the game-based learning group only [59]. These findings helped direct our design efforts when building CSpresso for binary counting. When designed well, AR/VR experiences can immerse the user in the virtual environment causing them to be less aware of their surroundings which may increase their confidence of performing binary math equations in front of their peers.

Game-based learning also shows promise in CS education at the K-12 level [62, 63, 64]. Comparing game and non-game versions of otherwise identical educational material demonstrated better results in the game version, effectively isolating gameplay as a significant factor [89]. Recent interest in computational thinking education promotes novel designs and approaches. Other projects exploring multistage game-based system for fostering computational thinking skills show positive results on student engagement [61, 65, 68, 69, 113, 125]. Similar parallels were found when designing CSpresso around an open exploration space with interaction elements meant for open-ended tinkering. The experience was designed to account for multiple play styles by having interaction elements display the results of their actions, and show how multiple actions stack together for a final answer that the student may change at any time during the task based on reviewing any of the feedback areas.

4.3 Method

4.3.1 Study Design

The study was a between-group design with two groups: learning in a physical environment (our control), and learning in a virtual environment (our treatment). Participants were placed randomly into the two groups. The control group had binary counting training with a live instructor in a physical environment, and the treatment group had binary counting training with interactive software in a virtual environment.

The two groups were randomly divided into smaller teams of five for effective training and participant management.

The null hypothesis of the experiment was that there is no measurable differences of the learning metrics between the control and treatment groups. The alternative hypothesis of the experiment was that there is measurable differences of the learning metrics between the control and treatment groups.

The independent variables in the experiment were whether the binary counting training of a participant is administered in a physical or virtual environment. The dependent variables were the participants' knowledge scores from their pre- and post-learning assessments, and participant perceptions on usability and engagement factors of the virtual environment training. The essential dependent variables were the learning metrics which are gathered as quantitative data. The exploratory dependent variables were the virtual treatment participants' perceptions on usability and engagement factors which were gathered as qualitative data to understand if rationale can be suggested for any differences of the quantitative results.

Curriculum for both groups was developed from a nationally recognized CS program, and taught by a certified CS instructor. The experiment was conducted for one day of an unrelated CS summer camp. Learning assessments were administered to participants before and after the experiment. Qualitative measures of the virtual participant usability and engagement metrics were gathered from semi-structured focus groups.

4.3.2 System

The design goal of the virtual learning environment was to take full advantage of the Oculus Quest VR headset's free roaming feature, which would allow the user to move through virtual space without entanglement by physical wires in the real world. The Oculus Quest was a standalone VR headset that gives stimulus input to the

user through a wireless headset and takes output from the user through wireless hand controllers [85]. It was an Android computer system that can connect to a developer's PC for software development, testing, and data input and output. The user could experience standing or sitting based VR experiences in the headset, and this system was a standing VR experience requiring 20' x 20' of empty room space for the user to move around the virtual learning environment (see Figure 4.1).



Figure 4.1 Treatment participants immersed in the virtual environment.

The software development environment used to build this system was the Unity real-time 3D development platform [116]. It was an integrated development environment specialized for the developer needs of real-time 3D applications including AR/VR educational technologies. Unity also was a multi-windowed development environment with some panes for visualizing and building the interactive 3D virtual environments, and some panes for programming in the computer language C# to create the functionality of the application. Other software packages were needed to create two-dimensional (2D) and 3D graphical and animation elements needed for the virtual learning environment. Autodesk Maya and Max were used for the 3D models

and animations. Adobe Photoshop and Substance Designer were used for the texture creation of the 3D models.

The virtual environment was presented as visuals through the left and right eye monitors of the headset. The headset tracks where the user was walking and looking in the virtual environment by recording the position and rotation of the user's head. This allowed the visuals to be updated in the left and right eye monitors. The hand controllers tracked where the position of the user's hands were in the virtual environment as well as the hand poses that the user created by moving their fingers across sensors on the hand controllers. Position and rotation data from the headset and hand controllers were recorded by the developer's software for analysis of the task time and movement of the users. 3D user interface elements in the virtual learning environment were also recorded for analysis of the user task time and error rates.

4.3.3 Stimuli

The stimuli to the participants were visual and interaction only, there was no audio stimuli. The virtual environment was visually presented as the user standing in a circular room with a waist high station in front of them with a user interface to give text directions to the user. The only part of the user that was represented visually in the virtual environment was their hands since that was their interaction point with 3D user interface. The "binary counting" station was interactive, allowing the user to grasp their virtual hands through virtual representations of pullable levels. All interactions required of the user were presented as a tutorial when the application first started (see Figure 4.1). Details of the software design are listed in the appendix (see all Figures in Appendix H and I).

CSpresso's virtual environment included stations with interactive consoles organized into a concentric circle, all sequentially placed in clockwise direction. The design followed the order of interaction from start to finish, in one circular loop. Each

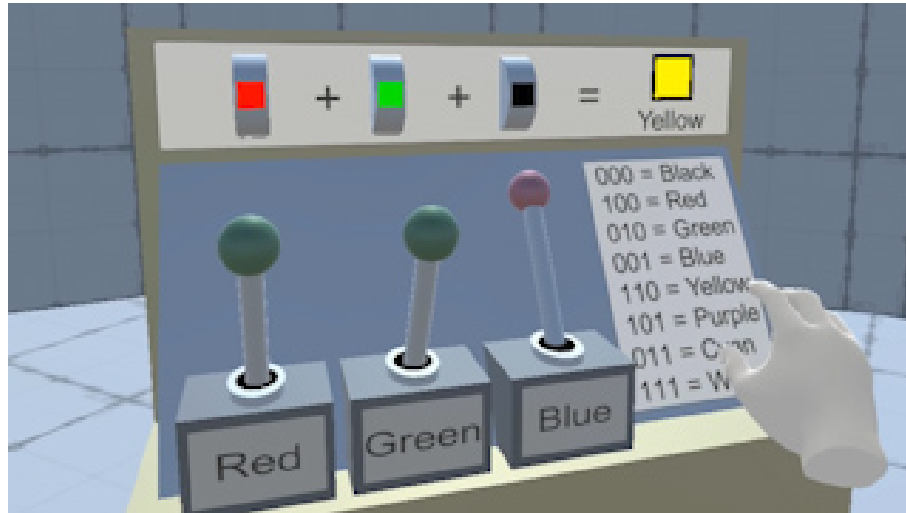


Figure 4.2 User interacting with the color station in the virtual activity.

station must be visited and interacted on by the user to complete a task, with the entire experience requiring the completion of seven progressive harder tasks involving solving binary counting problems.

There were five stations (task station, number station, color station, shape station, and output station) to interact with during a task, each with a set of levers that the user pulls to set binary values of either 0 or 1 disguised in various forms such as on or off, 0 or 2, red or green, and cube or sphere. Each task started with the user receiving directions to perform at the task station, which involved recreating the correct binary value to represent a number, color, or shape. To do so, the user must travel to several other, specialized stations to create the correct output and return it to the task station. For example, one task was to bring five yellow spheres back to the task station. The user must go to the number, color, and shape stations, respectively, pull on the correct levers, and created the correct number of required colored shapes (see Figure 4.2).

4.3.4 Participants

The participants were 34 middle school students (19 girls and 15 boys), from 5th to 8th grade (median 6th grade), participating in a 9-session Saturday CS camp. The students were randomly dividing into two classrooms at the beginning of the camp, and the binary counting session was held during their 7th Saturday. The students were randomly assigned in one room to be the control group, and the other room's students as the treatment group. Neither room's students were aware of the other room's assigned activity. This was done to minimize distractions, as recruiting only a subset of students from each room to participate in the treatment group might cause the control participants to complain that they could not partake in the novel activity. After data collection was completed for the day, the control participants were informed about the activity, and allowed to try out the treatment activity.

4.3.5 Procedure

For the study, a gymnasium was used (for the treatment activity), along with two classrooms (one for the teacher to lecture about binary counting to the control group; and one for interviewing treatment participants after completing their activity). The gymnasium was split into five 20ft x 20ft quadrants (using marking tape on the floor), one for each treatment participant per session (see Figure 4.1). Due to this configuration, we were able to run a maximum of five treatment participants per sessions concurrently.

The activity was developed for the study by reviewing CS Unplugged—activities designed to introduce computational thinking concepts to students without the use of computers [10]. It was decided to teach a binary counting lesson (specifically, the binary counting card lesson), which was a topic that was not covered in the CS camp. For the control condition, the teacher used the binary counting lesson from

CS Unplugged. For the virtual condition, the lesson was adapted into the CSpresso VR learning experience.

The control group had 15 participants (8 girls and 7 boys). Individuals from this group participated in a 45-minute session, which included taking a pre-assessment, a 20-minute learning activity, and a post-assessment. The learning activity was led by one of the researchers (i.e., the activity teacher), an experienced educator, with over a decade of practice teaching introductory computer science materials.

The treatment group had 19 participants (11 girls, 8 boys) divided into three groups of five and one group of four (as the researchers were only able to have five concurrent treatment participants active per session). These groups participated in a one-hour session, which included taking a pre-assessment, a 5 minute VR equipment training session (see Figure 4.3), a 20-minute VR learning activity using CSpresso (see Figure 4.1), a post-assessment, and a 10-minute focus group interview.

Before starting the sessions, all participants filled out a pre-test learning assessment with 12 fill-in-the-blank questions (see Figure C.1). Questions were used from the CS Unplugged binary card counting activity, and took about 15 minutes for students to complete [10]. After learning about binary counting, all participants were given the same questionnaire as the post-assessment. Changes in the participants' pre



Figure 4.3 Virtual treatment participants receiving equipment training.

and post assessments were used to understand the differences in the learning impact of the control and treatment conditions.

4.3.6 Measures

Learning Assessment Before starting the sessions, participants filled out a pre-test learning assessment with six open-ended questions (see Figure C.1). The questions tested participants understanding of the procedure for binary counting of increasing larger numbers. Questions also inquired about symbol systems, that the participants were not taught during the experiment, to understand if the knowledge was transferable. The assessment questions came from CSUnplugged [10]. After learning about binary counting in the experimental training session, participants were given the same questionnaire as the post-assessment. Changes in the participants' pre- and post-assessments were used to understand the differences in the learning impact of the conditions.

Usability Interviews Focus group interviews were conducted with all participants in the treatment group after they completed their post-assessments. The research team had more than 15 years of experience in HCI research and the researcher conducting the interviews was a certified CS teacher. The participants were accompanied by their CS teacher who they had known from the program. The researchers interviewed students in focus groups of five participants as this was the size of a session group and past research indicate that is an appropriate size for these activities with children [39, 31]. This allowed the students to feel more comfortable with their peers and also there was limited time and resources to interview two students at a time. Each group that was interviewed took 10 to 15 minutes to discuss the key questions outlined in the semi-structured protocol below. All interviews were recorded and transcribed for further analysis.

Semi-structured focus group protocol to probe participants' understanding of their user experience within the virtual treatment:

- What did you like? What was fun? Did you feel engaged?
- What did you dislike? What was challenging about VR?
- Did you learn anything while playing VR?
- Did this exceed your expectations?
- Would you hope to see or do something different?
- How easy/hard it was to use the controller?
- Was it easy/hard to select/manipulate objects?
- Were you dizzy? Did you feel uncomfortable? Sick?
- Did you find the tutorials helpful? Why? Or why not?
- Could you figure things out without a tutorial?
- Did you like physical movements?
- Did you like walking while learning/playing?
- Did you need to stop early?
- Where you comfortable for a whole time?
- Did you want to stay longer or less?
- Did you experience any blurriness?
- Would you like to play on a computer or a headset?

A three-stage coding process described by Cambell et al. was used for the measurement of intercoder reliability for semi-structured interviews [17]. The interview lead read through all interviews and generated a list of codes. A group of three researchers reviewed 10% of the transcripts and reached a minimum of 87% intercoder reliability. Once this was completed, the three researchers coded the remaining transcripts and counted code occurrences.

After consolidation, 13 codes were identified and grouped into three themes as shown below. Since the researchers conducted focus group interviews, the frequency of each code was counted as it appeared in each group's transcript, totaled up all group's code frequencies and ordered the codes within each themes as to their frequency totals. This gave an understanding to the dominant trends reported by the focus groups in each theme. As the resulting data are nominal/categorical, the frequencies were reported of the different codes; shown as total frequency per code for all participants from the treatment group.

Codes grouped into their themes:

1. User Emotions of the Virtual Experience:

Enjoying Immersion, Enjoying Physical Activity, Enjoying Learning, Feeling Bored, Feeling Distracted

2. Usability Suggestions for the Virtual Experience:

Adjustable Difficulty, More Content, Clearer Directions, Improve Interactions, Fix Broken Objects

3. Platform Issues of the Virtual Experience:

Blurry Vision, Disorientation, Headset Discomfort

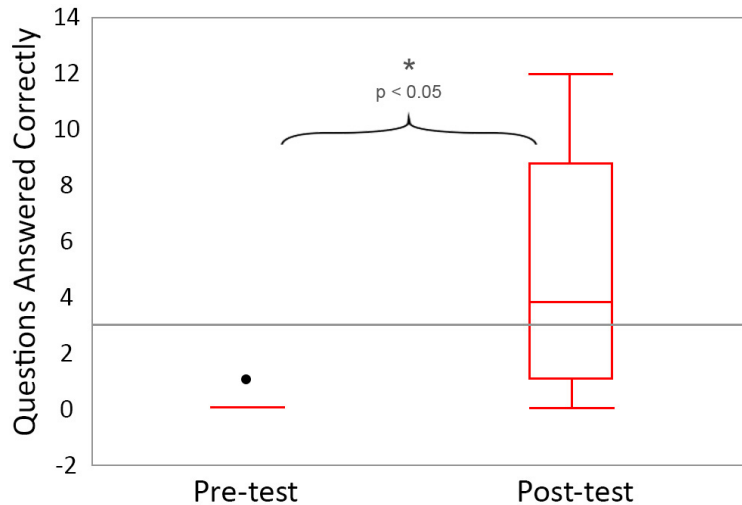


Figure 4.4 Control pre and post scores show knowledge difference.

4.4 Results

4.4.1 Pre and Post Learning Assessment Difference per Condition

To see if there was any affect by the interventions, analysis of differences within each condition (e.g., control pre-test vs. control post-test) was conducted. In the control group, middle school students ($n = 15$) were taught by a teacher how to count in binary up to three digits. In the treatment group, middle school students ($n = 19$) were taught by CSpresso how to count in binary up to three digits. Students were given a pre-test and post-test with 12 questions each involving counting in binary up to five digits. Here, “Questions Answered Correctly” (in Figures 4.4-4.7) all refer to the total number of questions a student got correct on either the pre-test of post-test. The minimum score was 0, and the maximum (perfect) score was 12. For all learning assessment analysis, Wilcoxon Rank Sum test with $\alpha = 0.01$ confidence was used, as the data was not normally distributed.

The control group participants did not do well in the pre-test, which is to be expected for participants with no prior knowledge in binary counting, but showed a statistically significant increase in their post-test scores ($W = 108, Z = -3.895, p <$

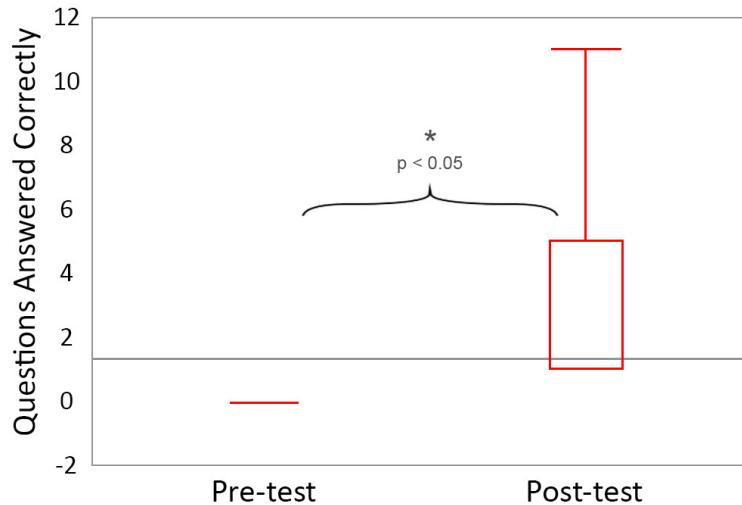


Figure 4.5 Treatment pre and post scores show knowledge difference.

0.01), suggesting that the teacher-led lecture helped them understand how to count in binary, up to five digits (see Figure 4.4).

The treatment group participants also did not do well in the pre-test, which is to be expected for participants with no prior knowledge in binary counting, but showed a statistically significant increase in their post-test scores ($W = 493, Z = 5.6786, p < 0.01$), suggesting that CSpresso helped them understand how to count in binary, up to five digits (see Figure 4.5).

4.4.2 Learning Assessment Differences between Conditions

To see if there were any differences between the classrooms, differences between condition (e.g., control pre-test vs treatment pre-test) were analyzed. The control and treatment condition participants were comparable at the beginning, with no measurable difference in their pre-test scores ($W = 241, Z = 1.7376, p = n.s.$), meaning that these students all started with the same inexperience in counting binary (see Figure 4.6).

After the learning activity (either a physical lecture or a virtual experience), there were no measurable difference in participants' post-test scores ($W = 286.5, Z =$

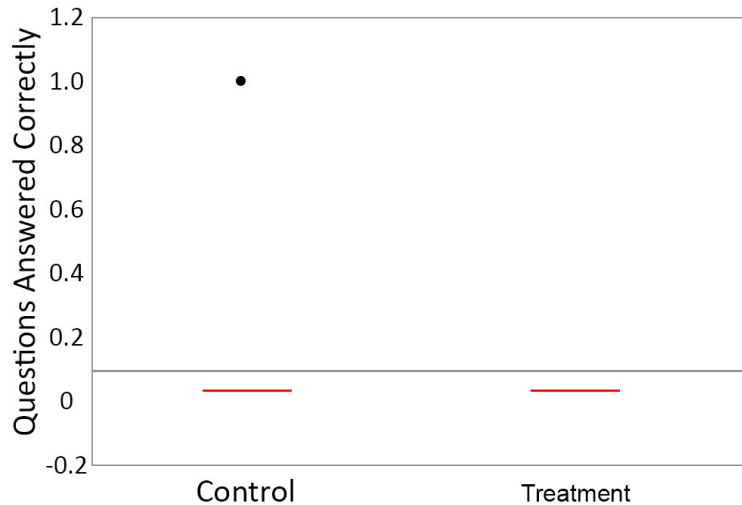


Figure 4.6 Control and treatment pre-test scores show no knowledge difference.

1.4875, $p = n.s.$) while the scores were much improved compared to their pre-test scores. This demonstrates that the physical lecture and the virtual activity were both effective in teaching their respective students how to count in binary. Examining the boxplot (see Figure 4.7) suggests that the control condition students did slightly better overall in the post-test compared to the treatment condition, but not enough to make a statistically significant difference.

Interview Codifications of Treatment Condition

Analysis of the interview data revealed three major themes: user emotions of the virtual experience, usability suggestions for the virtual experience, and platform issues with the virtual experience. For user emotions of the virtual experience, five codes appeared in the focus group interviews for a total count of 36 appearances in the interviews (see Figure 4.8). Of the five codes for the user emotions of the virtual experience theme, three were positive of the experience (enjoying of immersion, physical activity and learning of the experience) and two were negative of the experience (feeling bored and distracted). All three positive emotions about the experience were reported at higher rates (33.33%, 30.55%, 25%) than than the

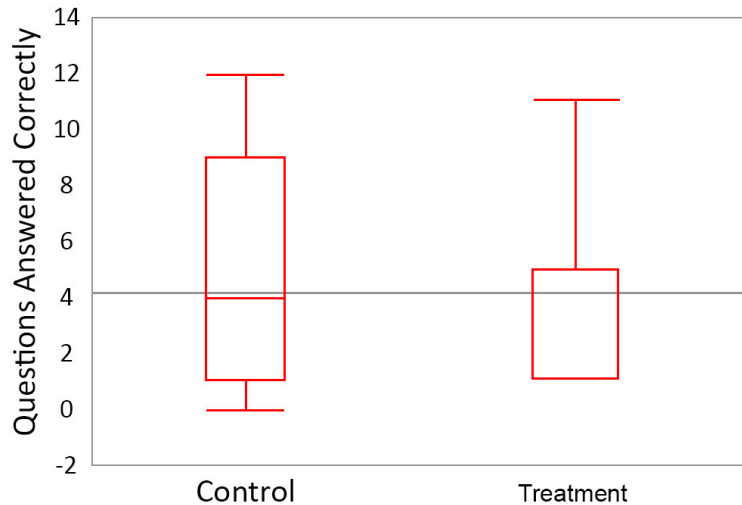


Figure 4.7 Control and treatment post-test scores show no knowledge difference.

negative emotions about the experience (5.6%). For usability suggestions for the virtual experience, five codes appeared in the focus group interviews for a total count of 38 appearances in the interviews (see Figure 4.9). For platform issues with the virtual experience, three codes appeared in the focus group interviews for a total count of 13 appearances in the interviews.

Participants reported feeling enjoyment by the immersion of the experience 12 times, which is 33.33% of the total reported counted codes for the user emotions of the virtual experience theme. Enjoyment of immersion covers topics of enjoying physically moving around the virtual space, and observing objects and performing the tasks that gave them the feeling of actually being in the experience.

Participants reported feeling enjoyed by the physical activity of the virtual experience 11 times, which is 30.55% of the total reported counted codes for the user emotions of the virtual experience theme. Enjoyment of physical activity covers topics of enjoying actively interacting with objects, such as throwing objects, pulling levers, picking up and moving objects with their virtual hands.

Participants reported feeling enjoyed by the learning of the experience nine times, which is 25% of the total reported counted codes for the user emotions of the

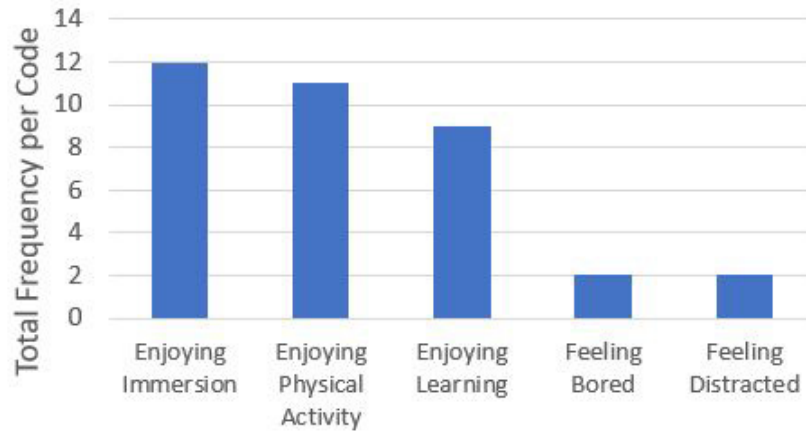


Figure 4.8 User emotions of the virtual treatment experience.

virtual experience theme. Enjoyment of learning covers topics of problem solving without any guidance, while in experience and/or retaining knowledge from the tutorial or experience.

Participants reported feeling bored by the experience two times, which is 5.6% of the total reported counted codes for the user emotions of the virtual experience theme. Feeling bored covers topics of expressing a frustration of not being challenged enough or the activities becoming too tedious.

Participants reported feeling distracted by the experience two times, which is 5.6% of the total reported counted codes for the user emotions of the virtual experience theme. Feeling distracted covers topics of being afraid of bumping into things, while trying to concentrate on tasks in the experience. Hearing classmates talking while in the experience.

Participants reported wanting adjustable difficulty for the experience 15 times, which is 39.5% of the total reported counted codes for the usability suggestions of the virtual experience theme. Adjustable difficulty covers topics of complaints about task difficulty, and expressing the need for more guidance in the experience.

Participants reported wanting more content for the experience eight times, which is 21.1% of the total reported counted codes for the usability suggestions of the

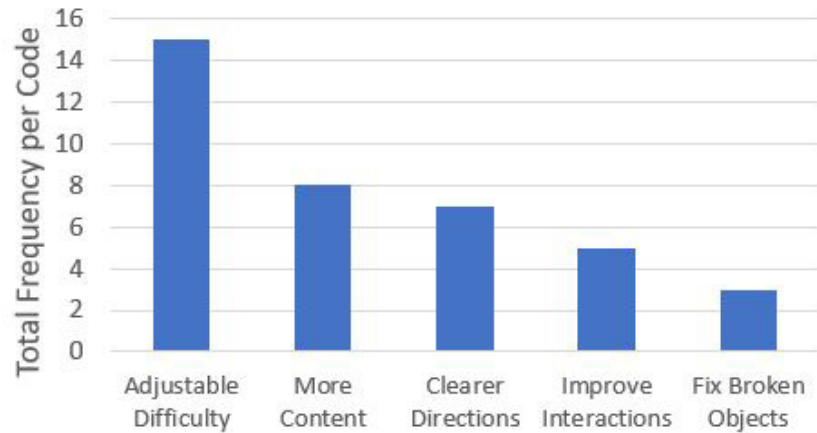


Figure 4.9 Usability suggestions for the virtual treatment experience.

VR experience theme. More content covers topics of suggesting or asking for more levels, different activities, characters, or scenarios.

Participants reported wanting clearer directions for the experience seven times, which is 18.4% of the total reported counted codes for the usability suggestions of the virtual experience theme. clearer directions covers topics of walking out of the boundary, pressing buttons that are instructed not to press, not following along with either in-game or pre-game tutorials.

Participants reported wanting improved interactions for the experience five times, which is 13.2% of the total reported counted codes for the usability suggestions of the virtual experience theme. Improved interactions covers topics of not liking how something works or looks in the experience.

Participants reported wanting to fix broken objects in the experience three times, which is 7.9% of the total reported counted codes for the usability suggestions of the virtual experience theme. Fixing broken objects covers topics of functions of different objects in experience not working correctly.

Participants reported blurry vision in the experience seven times, which is 53.8% of the total reported counted codes for the platform issues of the virtual experience theme. Blurry vision covers vision issues or trouble with fitting glasses into headset.

Participants reported disorientation in the experience four times, which is 30.8% of the total reported counted codes for platform issues of the virtual experience theme. Disorientation covers topics of disoriented during or after experience, complaints about no visible feet or legs, and jittering of the virtual hands.

Participants reported discomfort from the headset in the experience two times, which is 15.4% of the total reported counted codes for the platform issues of the virtual experience theme. Discomfort from the headset covers topics of uncomfortable, heavy feeling on the face from headset.

4.5 Discussion

The outcome of this user study was found to be highly rewarding to the treatment participants with a majority not wanting to stop playing CSpresso at their maximum play time of 20 minutes. The overall impression received from observing the treatment participants in the second study was that CSpresso, even in its preliminary state, was engaging and fun. Students made full use of the Quest's untethered feature, breaking out into victory dances and freely moving about in their 20 by 20 foot space.

4.5.1 Interpretation of Learning Assessments

The analysis of the learning assessments indicated the treatment group participants learned binary math just as well as the control group participants that were taught by the summer camp's instructor. This suggests that CSpresso can be as effective as an instructor-led lecture without the restrictions on instructor availability and locality. These results revealed that the CSpresso experience is educational, and suggests that it may have some benefits over traditional teaching methods.

The control and treatment condition participants both started off the same score that is close to zero. In other words, they did not know how to count in binary. After either a physical lecture or using the virtual educational experience,

students' post-test scores were significantly higher. However, there was no statistically significant difference between these groups' post-test scores, meaning that both the physical lecture and virtual educational experience led to similar outcomes when teaching the students how to count in binary.

The results of the learning assessments shows that the participants who learned binary math through the virtual educational experience were just as successful as those who learned from a certified CS instructor. This indicates that virtual educational experiences can be used as alternative teaching tools in CS education which can supplement traditional teaching methods enabling new learning methods for students in the classroom and at home.

4.5.2 Interpretation of Interview Data

Of the five codes for the user emotions of the virtual experience theme, the three positive emotions about the experience were reported 5-6 times more frequently than the two negative emotions about the experience. Since all three positive emotions are reported at a much higher frequency compared to negative experiences, it may suggest that the experience is engaging, immersive, and an impactful learning experience—all which point to success for this chapter's study of the virtual educational experience.

Of the five codes for the usability suggestions of the virtual experience theme, the most frequent was to make the experience more customizable to the user. This involves adjusting task difficulty and training time during the tutorial, and offering help during tasks if users get stuck. The second most frequent request was for more content, which is reasonable since this version of the experience had no high quality graphics and only focused on the interactions and user experience needed for learning the binary math material. Since then, extensive work was put into the graphics quality of the experience, which can be seen at artncoding.com (see all Figures in

Appendix H and I). The remaining codes dealt with refining the current experience by making the directions clearer, improving interactions, and fixing broken objects.

Of the three codes for the platform issues of the virtual experience theme, the most frequent issue was blurry vision, followed by user disorientation and discomfort of the headset. Since these are issues with the current hardware implementation, it is not worth discussing them and assume that these issues will be fixed with future hardware iterations. Some additional observations from listening to participants were:

Effortless and intuitive interaction Participants felt that learning was natural and easy. They liked to see their hand motions and the natural interaction through hand gestures. Most of all, they liked the ability to physically walk around in VR.

Request for more content Participants liked the provided activities and wanted to participate in more similar activities as they felt the task got redundant toward the end when they grasped the main concept taught by the activity.

Gender-specific feedback Male participants requested action-based and exciting events such as explosions while the female participants were happy with a calm and quiet virtual environment allowing them to take their time to solve the tasks.

Other Requests Participants wished to have a guide or a friendly helper during an experience and wanted to see more of their virtual body parts besides their hands. One student found the found the headset to be heavy.

4.5.3 Study Limitations

Experimental bias existed and could not be reduced from the influence that all participants were already registered for a CS summer camp. Both groups taught the participants to count up to three digits in binary and learning assessments checked

up to five digits in binary. Further training sessions and assessments may need higher amounts of binary digits to verify educational efficacy of both groups.

4.6 Conclusion

This chapter compared the efficacy of a traversable immersive virtual learning environment against live instruction in a physical learning environment. It explored the effects of a traversable immersive virtual environment on middle school students learning binary counting, which is an important computational skill for CS and STEM learners. Educational fields that are abstract in nature, such as CS and other STEM fields may find alternative teaching methods useful to maximize student opportunities to internalize and process the curriculum.

When designing AR/VR educational tools, having the user move through and interact with the virtual environment may help learners engage with STEM educational concepts. With this objective in mind, a CS educational VR experience, called CSpresso, was developed to teach students to count in a binary number system (see all Figures in Appendix H and I). User testing confirmed that the treatment group, who learned to count binary in a traversable virtual environment, were just as successful as the control group, who learned with live instruction in a physical environment. This evidence suggests that instructional delivery in a virtual environment with traversal of the spatial AR/VR interface offers comparable learning efficacy to the traditional physical environment.

CHAPTER 5
**EFFECT OF TRAVERSAL KINEMATICS ON EFFICACY OF
IMMERSIVE VIRTUAL LEARNING ENVIRONMENTS IN STEM
EDUCATION**

5.1 Introduction

As AR/VR technologies become more mainstream, educational technologies will increase use of AR/VR capabilities. User experience (UX) designers will need to understand the extent that these capabilities can impact a virtual learning environment. AR/VR technologies have the unique feature of a spatial interface, which is a system interface that is embedded into the virtual environment in 3D around the user. This enables a level of realism to computer system interfaces that can emulate physical interactions with a higher fidelity than 2D user interfaces on computer monitors. Understanding the benefits that spatial interfaces can bring to user learning and performance, and help UX designers develop better virtual learning environments using AR/VR technologies. The proposed experiment in this chapter seeks to isolate the interface components of traversal fidelity that are unique to AR/VR technologies and offer insight into their impact to user learning, performance, and usability preferences.

The goal of the chapter is to understand how the traversal characteristics of a spatial interface in a virtual environment influences the user's STEM learning performance. We examined if learning, retention, and engagement of CS educational concepts improve when users are exposed to iterations of that virtual environment in an AR/VR platform with controlled variations of spatial interface traversal. The traversal methods and their effects are explored with undergraduate CS student participants learning "bubble sort", which is an important computational skill for CS and STEM learners. Students that find educational topics within the STEM fields difficult to learn, may find alternative teaching methods useful to maximize

their performance and comprehension. When designing AR/VR educational tools, having the user move through and interact with the virtual environment may help learners engage with difficult to learn STEM concepts, and attract a more diverse population to the STEM fields.

This chapter examines the effect of varying the kinematic style of traversal within an immersive virtual environment on STEM learner performance. The previously presented studies (see Section 3.3 and Section 4.3), compared the effects of immersive virtual learning environments against physical instructor-led live lectures, but did not examine the effects of traversal variations within an immersive virtual learning environment. The two kinematic styles of traversal that will be compared are natural walking and hand controller-based walking. The learning objective will be a fundamental CS sorting algorithm called “bubble sort”.

This chapter presents the final of three studies examining how traversability affects user performance in a virtual learning environment. It compares the efficacy of two AR/VR traversal methods on learning performance within a virtual environment: natural walking and hand controller-based walking (i.e., with the user in a stationary, seated position). The research questions are:

- How does body kinematics of AR/VR traversal impact learner performance?
 1. How does body kinematics of AR/VR traversal impact learning?
 2. How does body kinematics of AR/VR traversal impact retention?
 3. How does body kinematics of AR/VR traversal impact usability?
 4. How does body kinematics of AR/VR traversal impact task time?

5.2 Related Work

Due to its focus on 3D user interfaces, the User-System Loop (USL) framework was selected to design and evaluate the AR/VR prototype built to teach the CS

sorting algorithm, bubble sort, for this chapter's study [60]. The essence of the USL framework is based on the model-view-controller design pattern of object-oriented programming [60]. The model is the simulation of the learning objective, while the view is the spread out amongst the virtual environment as the 3D visualization of the simulation, and the input are the physical devices on the users' head and hands that allow them to interact with the simulation. As such the AR/VR prototype followed model-view-controller design within a 3D virtual space to accommodate the evaluation principles of the USL framework.

When a system interface is displayed spatially in 3D around the user, the traversal fidelity of the interface may have a stronger impact on user performance [74, 75]. This is because the interface elements are not restricted to a 2D monitor that is completely contained within the user's field of view [60]. Interface elements can be placed in any location around and distance from the user. This increases the complexity of the decisions for the UX designer, so it is important to understand how traversal fidelity around a spatial interface can impact user performance in an immersive virtual learning environment.

A framework-based approach is needed to evaluate the effects of the spatial interface components on user performance in an immersive virtual learning environment, in particular how the fidelity or realism or a user's traversal affects their learning performance. A framework-based evaluation approach that has been designed specifically for 3D user interfaces is the USL as a system oriented adaption of Norman's Seven Stages of Action [74]. In this model, user interactions begin with actions that manipulate input devices, which are interpreted as sensory information to the system. The system alters the data and models underlying the simulation of objects, their physical attributes and behavior. The system then updates the rendering information going to the system's outputs connecting to the user's input

based on changes to the simulation's data and models. This information is processed by the user as stimulus to be perceived.

Each stage of the framework identifies components that affect the overall interaction and usability of the system. Component evaluation examines one component while keeping the other components the same to alleviate confounding variables, which yields an understanding of best practices to use a combination of components to build a desirable system. Using a controlled experiment structure results in general knowledge applicable to a wider range of spatial interface design patterns. This component evaluation approach requires consideration to define the components that affect the system's stage of action.

McMahan et al. described a method to define the components within a USL in terms of fidelity, or realism including three categories of interaction fidelity, scenario fidelity and display fidelity [74, 75]. This study will be examining the virtual environmental factor of traversal fidelity within the USL framework as an interaction fidelity, which is defined as "the objective degree of exactness with which real-world actions are reproduced in an interactive system" [74, 75]. This study will be examining the fidelity of user traversal fidelity through the framework of biomechanical symmetry with its real-world counterpart.

Biomechanical symmetry is defined as "the objective degree of exactness with which real-world body movements for a task are reproduced during interaction", and can be further divided into subcategories of Anthropometric symmetry (IBA), and Kinematic symmetry (IBK) [74, 75]. IBA is the degree of fidelity which body parts involved in a real-world task are required by an interaction technique. IBK is the degree of fidelity which a body motion for a real-world task is recreated during an interaction technique. This study will examine the fidelity difference of IBK, while holding still the fidelity of IBA within the interaction biomechanical symmetry of the virtual environment factor of traversal fidelity of a spatial interface.

Traversal tasks have been lightly researched in relation to general or STEM based virtual learning environments, as most research focuses within the training scenarios of industrial, military, or naval traversal tasks. Mas et al. developed a VR multiplayer game for traversal skill training of workers in complex industrial facilities. They found that VR makes it possible to “multiply the number and duration of situations that learners can experience to better consolidate their skills”, which would be a beneficial effect if it can be generalize to STEM education [73]. Jingxian et al. found that the simulation of ship motion within a 3D virtual environment in VR improved the traversal training and wharf traversal assessment of future naval officers, and suggested that this may be helpful to other learning objectives of these officers which includes STEM areas [47]. No prior research was found examining how traversal interfaces can impact a general learning or a STEM learning task within a virtual environment, which is what this study will seek to find insights, but first we must identify proper traversal and interface techniques for AR/VR applications.

AR/VR applications have different demands for a user interface than monitor-based applications, which led Weib et al. to conduct a quantitative user study to identify advantages and disadvantages of 2D, 3D, and speech based user interfaces for virtual environments [119]. They found that 3D interfaces have higher ratings for natural and intuitive inputs along with better immersion into the experience but that 2D interfaces are easier to learn and comprehend. This lead the design of the study’s interface as a mixture of 2D and 3D elements to attempt to gain the advantages and minimize the disadvantages of both techniques. Lorenz et al. studied how the feeling of “being” in a virtual environment, called presence, are determined by the level of immersion and the style of traversal [72]. They simulated natural walking using a Wii Balance Board and a Kinect Sensor, and found that the more natural method of walking using the Kinect Sensor gave a stronger sense of presense to the

participants. This study would like to confirm if that stronger sense of presence can aid in a learning task in a virtual environment as well.

Traversal tasks within virtual environments can be problematic for users to process. Kheddar et al. approached these traversal task issues with a proposed traversal control algorithm based on the behavior of how humans move their head while intuitively exploring the real world [53]. Their psychology review of how human's process a new environment in the real world lead to design decisions in the study on how to build the 3D representation of the list in the virtual world. Kruijff and Riecke did an extensive review of spatial traversal interfaces allowing for locomotion through a virtual environment [58]. They examined the basics of traversal, including the user's psychological factors of exploration and travel inquiry. From these theoretical foundations, a practical framework was established and is the basis for the two styles of traversal devised in this study, natural walking and hand-controller based walking. As practical solutions for AR/VR interfaces emerge, well-research pedagogical practices should be identified to help design the virtual learning environment.

Modern CS pedagogical practices may be a good educational research area to find use cases that can be generalized to larger STEM areas. Multidisciplinary approaches to active learning scenarios, that simulate constructivist learning environments, and integrate CS and computational thinking with other disciplines have shown a positive impact on student outcomes. A study investigating the effects of a math, dance, and music program suggested that besides the increased CS knowledge, students showed increased interest in STEM education [106]. Courses with computational thinking learning objectives that applied scientific computation resulted in student reporting of stronger interest in pursuing CS education [38]. Similarly, Goode et al.'s "Exploring Computer Science" program combines content knowledge with instructional techniques in a professional development program,

makes a strong case for empowering teachers to introduce active learning in settings where traditional curricula have proven to be inadequate [33]. These studies indicate that virtual learning environments designed for active learning scenarios that encourage constructivism may help improve STEM educational practices.

Previous research has looked at the challenge of increasing the learning and interest of STEM students in CS using immersive technologies [99, 32, 88, 128]. In a study by Reuter et al., the use of AR/VR to teach CS showed that technology makes the learning material less abstract and complex using a more approachable technology [99]. They argued that the application of AR/VR techniques to teaching software engineering in higher education may alleviate learning obstacles attributed to its abstract and complex nature. Of particular interest, they point out that virtual simulations of system processes may appear more tangible to students, which guided the design principles of the prototypes presented in this dissertation. Gokhale demonstrated a teaching style that used the inherent students' interest in technology to teach and connect them to CS concepts [32]. Their approach utilized evidence-based reasoning of questions for students to understand abstract CS concepts by exploring the ideas of how the concept is applied to their favorite technologies. Both research approaches found favorable methods for making abstract CS concepts for STEM students more concrete, but they did not identify specific HCI factors that may have contributed to these learning and engagement outcomes, which is the agenda for this chapter's study.

When software requirements and constraints limit the use of the Embodied Interaction concept, then AR/VR technologies could simulate aspects of the physical objects to still enable the benefits of user interactions with physical objects or environments. AR/VR educational technologies using headsets and hand controllers can simulate aspects of the physical objects and environments that may offer learning benefits to STEM education by combining ideas from embodied cognition and

embodied interaction. The AR/VR learning environment tested in this chapter’s study were designed to simulate the sensorimotor experiences that a learner would have while using their body to learn about the world around them, and to encourage the user to interact and explore the virtual environment that is presented to them.

5.3 Method

5.3.1 Study Design

The study was a between-group design with two groups, a control and a treatment, that both learned the “bubble sort” algorithm in a virtual environment. The control group had to stand still and use the hand controller to move through the 3D representation of a list as they sorted its elements. While the treatment group was allowed to physically walk through a 3D representation of a list as they sorted its elements. The control group was given the hand controller interaction, since traversing an environment with a hand controller is typical in video games, whereas physically walking to traverse a virtual environment is less standard, i.e., more experimental. The study compared the learning, retention, task time, engagement, and usability measures between the conditions and interviewed all participants with open-ended questions to understand how the traversal characteristics of a virtual environment improves the users’ learning experience.

The null hypothesis of the experiment was that there are no differences of the learning, retention, usability, and task time metrics between the control and treatment groups’ movement interface of traversing the virtual learning environment. The alternative hypothesis of the experiment was that there are differences in the learning, retention, usability, and task time metrics between the control and treatment groups’ movement interface of traversing the virtual learning environment.

The independent variables were kinematic symmetry of the virtual environmental traversal interaction and demographics. There were two groups for the

traversal interaction independent variable based on how a participant is allowed to traverse the virtual environment. Demographics collected for this study represent control variables, and were participant gender, participant age, participant country of origin, and participant corrective lens usage. The dependent variables were the participants' knowledge scores from their pre, post, and retention learning assessments, total task and sub task times, error rates of tasks completed, and participant perceptions on usability and engagement factors of the virtual environment training.

5.3.2 System

The design goal of the virtual learning environment was to take full advantage of the Oculus Quest VR headset's free roaming feature, which would allow the user to move around without entanglement by physical wires in the real world [85]. The Oculus Quest was a standalone VR headset that gives stimulus input to the user through a wireless headset and takes output from the user through wireless hand controllers [85]. It was an Android computer system that could connect to a developer's PC for software development, testing, and data input and output. The software was designed as a standing VR experience requiring 20' x 6' of empty physical space for the user to move around the virtual learning environment (see Figure 5.1).



Figure 5.1 Participants immersed in the virtual bubble sort trainer.

The software development environment used to build this system was the Unity development platform [116]. It was an integrated development environment specialized for the developer needs of real-time 3D applications including AR/VR educational technologies. It was a multi-windowed development environment with some windows for visualizing and building the interactive 3D virtual environments, and some windows for programming in the computer language C# to create the functionality of the application. Other software packages were needed to create 2D and 3D graphical and animation elements needed for the virtual learning environment. Autodesk Maya was used for the 3D models and animations. Adobe Photoshop and Substance Designer were used for the texture creation of the 3D models.

The virtual environment was presented as visuals through the left and right eye monitors of the headset. The headset tracked where the user was walking and looking in the virtual environment by recording the position and rotation of the user's head and hands. This allowed the visuals to be updated in the left and right eye monitors. The hand controllers tracked where the position of the user's hands were in the virtual environment as well as the hand poses of the user by moving their fingers across sensors on the hand controllers. Position and rotation data from the headset and hand controllers were recorded by the software for analysis of the task time and movement of the users. 3D user interface elements in the virtual environment were also recorded for analysis of the task time and error rates of the user.

5.3.3 Stimuli

The stimuli to the participants were visual and interaction only, there was no audio stimuli. The virtual environment was visually presented as the user standing in an empty landscape with a waist high station in front of them with a user interface to give text directions to the user. The only part of the user that was represented visually in the virtual environment was their hands since that was their interaction

point with 3D user interface. The “bubble sort” station was interactable by allowing the user to push their virtual hands through virtual representations of push buttons. All interactions required of the user was presented as a tutorial when the application first starts (see Figure 5.1). Details of the software design are listed in the appendix (see Figures in Appendix H and I).

The virtual environment included a waist-high station, that grew length-wise with the size of the list to sort (see Figure 5.2). The station has an interactive console to give directions to the user and allowed the user to sort elements in the list and to move through the list. The console had a next and swap button to enable those actions to the user, and it had a small 2D representation of the list for ease of the user to understand all the elements and their relative amounts.

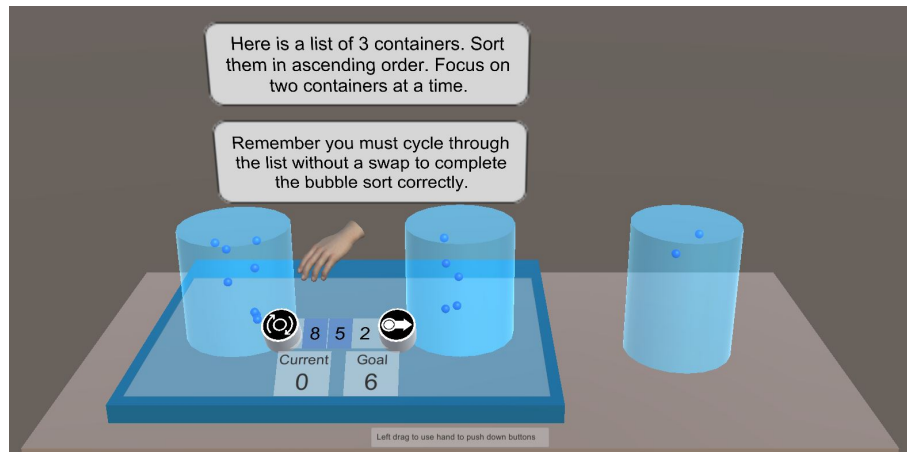


Figure 5.2 Console user interface of the virtual bubble sort activity.

At the beginning of each task, the station grew to the size of the list, the console gave directions to the user, and the user must move the console sequentially through the list deciding to swap the two active elements or to move to the next. When the user moved the console to the end of the list, and pushed the next button, then the console returned to the beginning of the list. Only when the user moved through all elements in the list and not swap any elements did the console check if the list is

in order. There are a total of seven tasks that should take the user between 15-30 minutes to complete (see Figure 5.3).

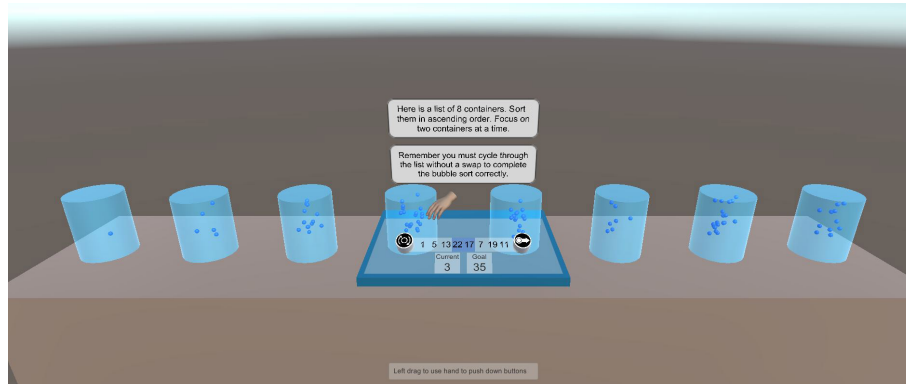


Figure 5.3 Station grows to accommodate larger lists.

5.3.4 Participants

Participants were gathered from the researchers' undergraduate classes for 5% extra credit. The participants were 42 undergraduate information technology (IT) students, of which 14.3% were female and 85.7% were male. Participant ages ranged from 18-36 years old (mean 21.55, median 21, and standard deviation 3.467). Demographics were gathered from a pre-assessment survey asking for participants' age, gender, ethnicity, prescriptive lens usage, and experience with AR/VR technologies (see Figure D.1).

Table 5.1 Control Group Details

Groups	Participants	Immersion	Anthropometric	Kinematic
Control	21	Virtual Reality	Standing	Hand Controller
Treatment	21	Virtual Reality	Standing	Physical Walking

5.3.5 Procedure

The participants were randomly assigned to one of the two groups, and came in for their learning sessions on separately assigned one hour time slots in one of the five experiment days to avoid participant interaction between groups during the study (see Table 5.1). The control group used a virtual learning environment with a hand controller based traversal interface teaching undergraduate students ($n = 21$) how to bubble sort lists from three to eight elements. The treatment group used a virtual learning environment with a natural walking traversal interface teaching undergraduate students ($n = 21$) how to bubble sort lists from three to eight elements. Group sizes were based on a power analysis to estimate minimum sample size required for an experiment, given a desired significance level (5%), effect size (default 80%), and statistical power (default 80%) [76].

Before starting the sessions, all participants were informed on the purpose and design of the study and asked to fill out the pre-assessments including a consent form, a demographic survey, and a learning assessment. Learning assessments had four questions involving bubble sorting lists from three to six elements. Training sessions were conducted in a virtual learning environment composed of six tasks that the participants needed to complete to finish the training. Each task involved bubble sorting a progressively longer list, where the first task involves sorting a list of three elements, and the final sixth task involves sorting a list of eight elements.

For both conditions, participants were provided with a demonstration of the Oculus Quest VR system, and then fitted with the headset and hand controllers. The participants spent 20 minutes in the VR interactive lesson, where they interacted with the “bubble sort” station and the console by pushing their virtual hands through virtual representations of push buttons, which was part of the tutorial presented to the participant when the application first started (see Figure 5.1). Control group participants were trained to use the thumb stick on the hand controller to virtually

walk through the 3D representation of a list of as elements as they learned the bubble sort algorithm. Treatment group participants were trained to physically walk through the 3D representation of a list of elements as they learned the “bubble sort” algorithm.

After the learning session, the participants were asked to fill out a learning assessment, a simulator sickness assessment, and a usability assessment. The participants continued participation remotely for the retention assessments, which were the learning assessments administered one day, one week, and one month after the treatment. The learning assessment was designed to be taken in under 10 minutes since it needed to be taken five times over the course of the experiment. All assessments were processed as digital forms to make the pre, post, and three retention assessments easy for the participants to fill out and the researchers to analyze.

5.3.6 Measurements

The measurements were designed to gather data on the learning, retention, usability, and task time metrics of the participants in the two groups. Learning measurements were taken as pre-assessment, post-assessment, and at three later dates to examine learning and retention metrics. Usability measurements were taken as post-assessment to examine usability metrics. Task time measurements were taken during the treatment session to examine task time metrics.

Learning Assessment The learning assessment had four multiple choice questions and test participants understanding of the procedure for bubble sorting progressively longer lists of elements (see Figure E.1). The multiple choice questions came from two popular computer science educational websites called geeksforgeeks.com and proprofs.com [101, 96]. The multiple choice questions were pilot tested and refined on five undergraduate CS students.

Simulator Sickness Assessment The simulator sickness assessment had 15 questions on a Likert-type scale (see Figure F.1) and an open-ended response question. The assessment was originally developed by Dr. Berbaum in 1993 and used extensively in aviation simulation studies and within the NJIT MIXR lab [52].

Usability Assessment The usability assessment had four sections of questions: usability, attention, spatial awareness, and presence. Survey sections were comprised of Likert-type scale questions on a seven point scale each followed by a open-ended response question that allowed the participants to explain their answers in more depth (see Figure G.1). Questions were designed to probe participant experiences with the immersion, traversal, visual fidelity, and user experience of the virtual learning environments. The usability questions were developed from previous experiments in the NJIT MIXR lab, and refined by one round of pilot testing on five undergraduate CS students. Participant responses were aggregated and analyzed for user experience trends in the virtual learning environments.

Open-ended Usability Questions Due to the large number of participants, and the limited number of researchers, interviews were conducted as open-ended questions listed in the usability assessment. There were four constructs to evaluate in the assessment: *general usability*, *presence*, *spatial awareness*, and *attention* [71]. Each construct had a section of the usability survey that contained a set of Likert-type questions, with an open-ended question asking for the participants' thoughts and rationale for choosing their previous response(s). The *general usability* construct was the broadest, and had eight Likert-type and four open-ended questions. The other three constructs were more specialized and had four Likert-type and one open-ended question, each. This allowed for gathering qualitative data that could be codified without having to interview each participant individually.

A three-stage coding process was used as described by Cambell et al., for the measurement of intercoder reliability for semi-structured interviews [17]. The interview lead read through all open-ended responses in the usability assessment and generate a list of codes. A second researcher reviewed 10% of the open-ended responses and reached a minimum of 87% intercoder reliability with the interview lead, which was 90% intercoder reliability. Once this is completed, both researchers coded the remaining open-ended responses and counted code occurrences.

Likert-type scale usability questions with statistically significant differences between the control and treatment had their open-ended responses analyzed to suggest rationale for differences between the groups. Means of construct group of questions showed no statistically significant difference, and only one usability question had a statistically significant difference, “How much did you enjoy moving your body”. After consolidation of codes on this usability question, four codes were identified. The frequency of each code was counted as it appeared in each participant’s usability assessment, totaling up all participants’ code frequencies and ordering the codes within each themes as to their frequency totals. This gave an understanding to the dominant trends reported by the participants. As the resulting data are nominal/categorical, we reported on the frequencies of the different codes (e.g., histograms); shown as total frequency per code for all participants from all treatments.

Codes generated for the statistically significant usability question:

1. Embodied Interaction Enjoyment:

Participants reported positive feelings of their computer interactions involving body kinematics.

2. Embodied Interaction Improvement:

Participants reported negative feelings of their interactions involving body kinematics and/or suggested improvements.

3. Embodied Cognition Enjoyment:

Participants reported positive feelings of their learning experience within the virtual environment involving body kinematics.

4. Cyber Sickness:

Participant reported feelings of nausea, feeling ill, or feeling a mismatch of cues between the body's actual motion and the mind's perception of that motion.

5.4 Results

5.4.1 Pre and Post Learning Assessment Difference per Condition

To see if there was any learning affect by the interventions, analysis of learning differences within each condition (e.g., natural walk pre-test vs. natural walk post-test) was conducted. The mean learning assessment scores per treatment show general trends of learning in the treatments over the course of the study (see Figure 5.4). The minimum score is 0, and the maximum score is 4. A repeated measurement analysis was conducted by modeling the discrete data of the five learning measurements and then running the Friedman test on the modeled data. No statistically significant differences of the five learning measurements between the groups was found ($F = 1.2058, n = 41, p = n.s.$). For all learning assessment analysis, the non-parametric Wilcoxon Rank Sum test with $\alpha = 0.01$ confidence was used, as the data was not normally distributed. When stated in the figures, "Questions Answered Correctly" labels refer to the total number of questions a student got correct on either the pre-test, post-test, 1 day retention-test, 1 week retention-test, or 1 month retention-test.

The control group participants did not do well in the pre-test, which is to be expected for participants with little-to-no prior knowledge of the bubble sort algorithm, but showed a statistically significant increase in their post-test scores ($W = 344.5, n = 21, p = 0.007$). This suggests that the virtual learning environment

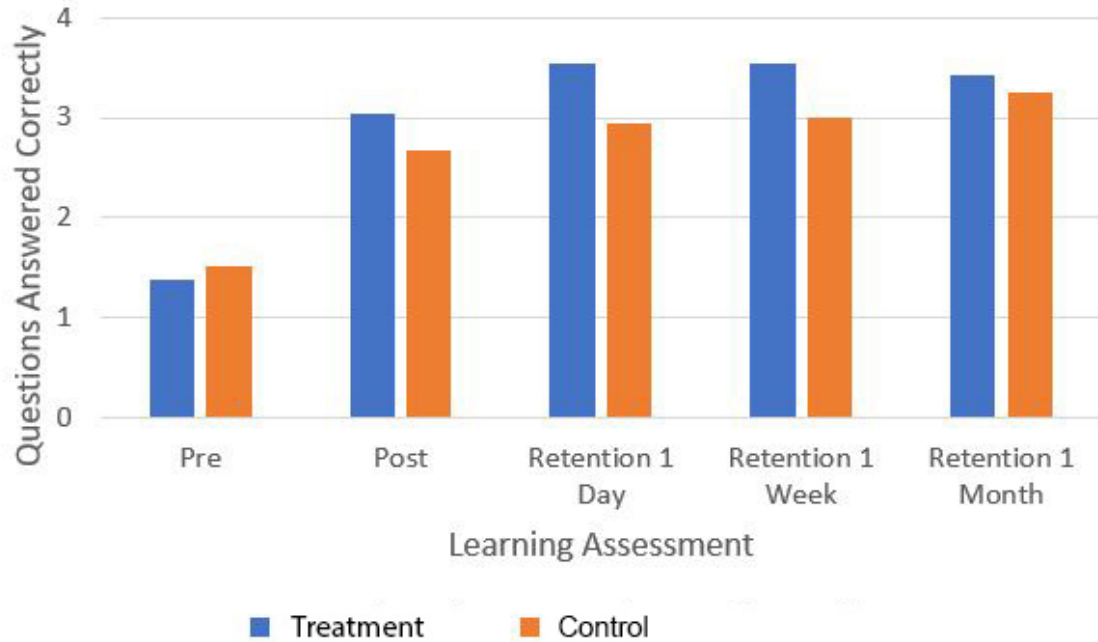


Figure 5.4 Mean learning assessment scores per condition.

with hand-controller traversal interface helped the participants understand how to implement a bubble sort algorithm on a list up to six elements (see Figure 5.5).

The treatment group participants also did not do well in the pre-test, and also showed a statistically significant increase in their post-test scores ($W = 291.5, n = 21, p < 0.001$). This suggests that the virtual learning environment with the natural walking traversal interface helped the participants understand how to implement a bubble sort algorithm on a list up to six elements (see Figure 5.5).

5.4.2 Pre to Post Learning Assessment Differences between Conditions

To see if there were any learning differences between the control and treatment, analysis of learning differences between each condition (e.g., natural walking pre-test vs hand-controller movement pre-test) were analyzed. Participants from both groups started off the same, without any statistically significant difference between their pre-test scores ($W = 437.5, n = 42, p = n.s.$). This meant that these participants

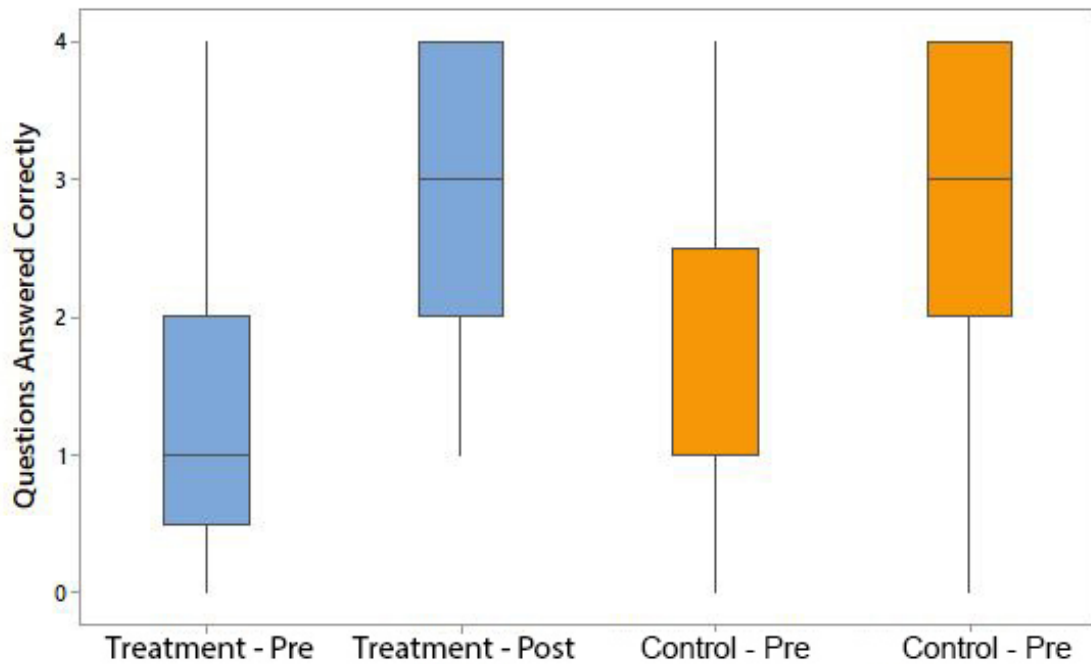


Figure 5.5 Pre-test and post-test learning assessment differences per condition.

all started off the same inexperience in regards to the bubble sort algorithm (see Figure 5.5).

After the learning activity, there were no statistically significant difference in participants post-test scores between the control and treatment groups ($W = 481.0, n = 42, p = n.s.$). This demonstrates that both the natural walking and hand-controller traversal interface were both effective teaching the respective participants how to implement a bubble sort algorithm. Examining the mean assessments scores and the boxplots of the two conditions (see Figures 5.4 and 5.5), suggested that the control group participants knew a small amount more about the “bubble sort” algorithm in the pre-test and knew a small amount less in the post-test compared to the treatment group participants.

Upon further analysis, there was a statistically significant difference between the learning improvements from the pre-test to the post-test of the two groups. The estimate of difference in the population medians was 1, and the confidence interval

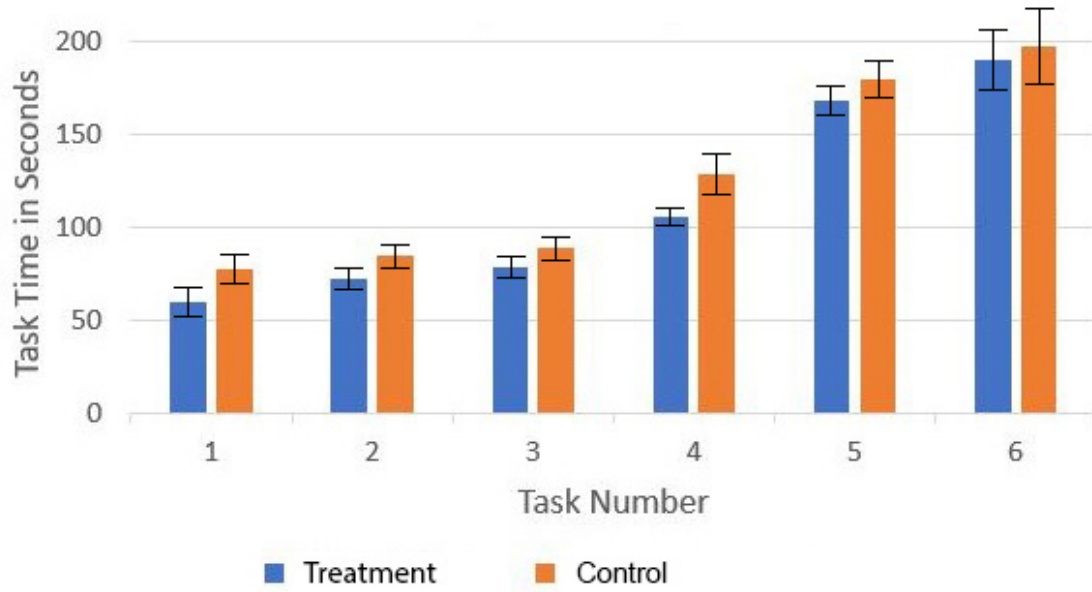


Figure 5.6 Mean task completion time per condition.

was (0, 2) with an achieved confidence of 95.11%. The treatment group participants did statistically perform significantly better than the control group participants when comparing the differences between their pre-test and post-test learning assessment scores ($W = 535.0, n = 42, p = 0.037$). This suggests that the virtual learning environment with natural walking traversal interface helped the participants learn the “bubble sort algorithm” better than with the hand controller traversal interface.

5.4.3 Task Time Differences between Conditions

To see if there was any task time affected by the interventions, analysis of task time differences between each condition was conducted. The mean task completion times per group showed general trends of task completion time increasing as the list required to sort got longer per task over the course of the training session (see Figure 5.6). The treatment group participants had a mean session time of 11.42 minutes and the control group participants had a mean session time of 12.65 minutes. For all task completion time analysis, the non-parametric Mann-Whitney test was used, as the data was not normally distributed. Outliers (that were two standard deviations away

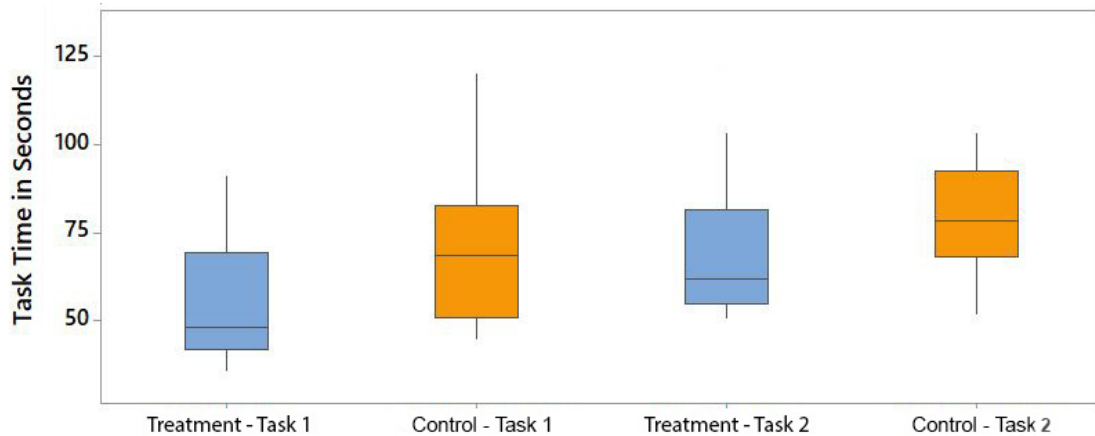


Figure 5.7 Task 1 and 2 completion time comparisons per condition.

from the mean—a threshold that can be considered “unusual” [67]) were removed from the task time data-sets prior to statistical analysis [25]. For thoroughness, analyses were performed without removing outliers and using the Mann-Whitney test as recommended by Bakker and Wicherts [5], but no differences were detected in any of the final results.

For task 1, the estimate of difference in the population medians was -12, and the confidence interval was (-28, -2) with an achieved confidence of 95.11%. The treatment group participants completed task 1 with statistically significant difference in the time to completion compared to the control group participants ($W = 308.5, n = 41, p = 0.018$) (see Figure 5.7). For task 2, the estimate of difference in the population medians was -12, and the confidence interval was (-23, 0) with an achieved confidence of 95.11%. In addition, the treatment group participants also completed task 2 with statistically significant difference in the time to completion compared to the control group participants ($W = 286.5, n = 37, p = 0.025$) (see Figure 5.7). This suggests that the virtual learning environment with the natural walking traversal interface helped the participants complete their “bubble sort algorithm” tasks faster than with the hand controller traversal interface.

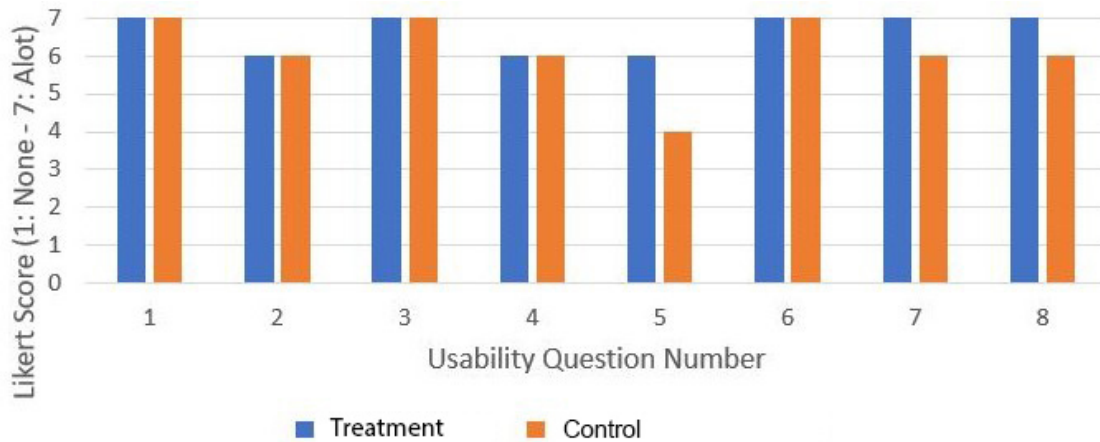


Figure 5.8 Median usability scores per condition.

5.4.4 Usability Assessment Differences between Conditions

To see if there was any usability affect by the interventions, analysis of usability differences between each condition was conducted. The non-parametric Mann-Whitney test was used for all usability survey analysis of the Likert-type scale responses, as the data was not normally distributed. All questions within the attention, spatial awareness, and presence sections had no statistically significant differences to report (see Figure 5.8). Within the usability section of the usability survey, seven of the eight Likert-type scale questions showed no statistically significant difference between the two conditions (see Figure 5.8). The fifth usability question, “How much did you enjoy moving your body while learning?”, did have statistically significant difference with the treatment group reporting a higher satisfaction response ($W = 528.0, n = 42, p = 0.037$) (see Figure 5.9). The estimation of difference in the population medians was 1, and the confidence interval was (0, 2) with an achieved confidence of 95.03%.

Analysis of the open-ended responses for the “How much did you enjoy moving your body while learning?” usability question revealed four major codes to report on: embodied interaction enjoyment, embodied interaction improvement, embodied cognition enjoyment, and cyber sickness (see Figure 5.10). Total code count for

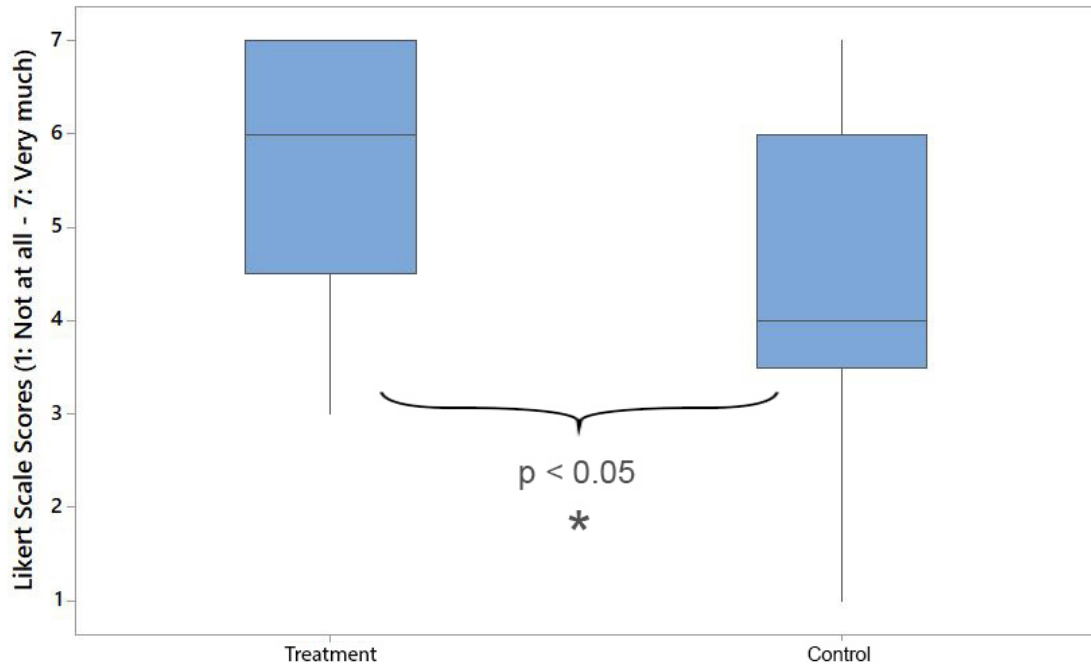


Figure 5.9 "Enjoy moving your body" question differences between conditions.

both treatments was 43, with 22 total code count for treatment group and 21 total code count for control group. Enjoyment of embodied interactions covered topics of participants responding positively about the body kinematics involved with the computer interactions. Improvement suggestions or negative feelings of embodied interactions covered topics of participants responding negatively and/or offering improvement suggestions about the body kinematics involved with the computer interactions. Enjoyment of embodied cognition covered topics of participants responding positively about the body kinematics involved with learning the subject matter. Feelings of motion sickness covered topics of nausea, stomach pain, head pain, light headiness, and psychological uneasiness with feeling a difference between what the body parts are doing and what the mind thinks the body parts are doing.

Treatment group participants reported enjoyment or positive feelings toward the embodied interaction experiences of the virtual learning environment eight times, which is 36.4% of the total reported counted codes for their treatment. Control

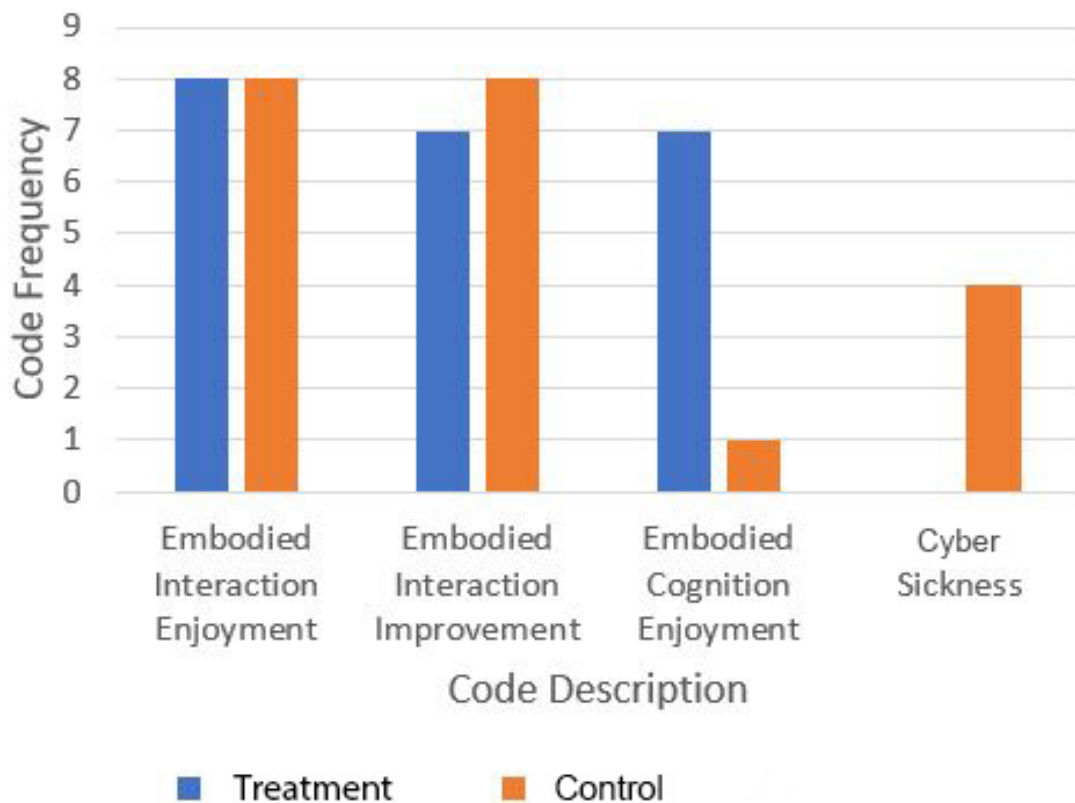


Figure 5.10 "Enjoy moving your body" codification differences per condition.

group treatment participants reported enjoyment or positive feelings toward the embodied interaction experiences of the virtual learning environment eight times, which is 36.4% of the total reported counted codes for their treatment. Treatment group participants expressed positive statements about being about to physically achieve a goal, interacting with a clean UI, appreciated not sitting still, wanted more body movements incorporated into the experience, enjoyed moving their body, and enjoyed experiencing a new type of interaction experience. Control group participants expressed positive statements about interesting experiences with their first time in VR, moving their hands in VR is impressive and realistic, enjoyed moving through the environment, and enjoyed standing better than sitting.

Treatment group participants reported improvement suggestions or negative feelings toward the embodied interaction experiences of the virtual learning environment

seven times, which is 31.8% of the total reported counted codes for their treatment. Control group participants reported improvement suggestions or negative feelings toward the embodied interaction experiences of the virtual learning environment eight times, which is 36.4% of the total reported counted codes for their treatment. Improvement suggestions or negative feelings of embodied interactions covered topics of participants responding negatively and/or offering improvement suggestions about the body kinematics involved with the computer interactions. Treatment group participants expressed negative statements and/or improvements about walking becoming cumbersome as the list got larger, it can become annoying to walk all the way back to the beginning of the list, it was getting tiring toward the end of the experience, it would be a good feature to allow a fast forwarding movement through the list, and that the walking through the list can be slower than what the participant wants to mentally move through the list. Control group participants expressed negative statements and/or improvements about that they would like to walk around the list, that they would want to sit me down instead of stand, whole body movements would be more immersive, wanted to use their legs in the interaction.

Treatment group participants reported enjoyment or positive feelings toward the embodied cognitive experiences of the virtual learning environment seven times, which is 31.8% of the total reported counted codes for their treatment. Control treatment participants reported enjoyment or positive feelings toward the embodied cognitive experiences of the virtual learning environment one time, which is 4.5% of the total reported counted codes for their treatment. Enjoyment of embodied cognition covers topics of participants responding positively about the body kinematics involved with learning the subject matter. Treatment group participants expressed positive statements about being more of a physical person, needing to walk and talk through a lesson, that they learn by doing, walking allows them to understand the concept quickly, enjoying the ability to stretch, increased comprehension of iteration and

computer processes, and gave them more of an accomplishment. Control group participants expressed positive statements about moving their body makes it easier to understand the content.

Treatment group participants reported feelings of cyber sickness by the virtual learning environment zero times, which is 0.0% of the total reported counted codes for their treatment. Control group participants reported feelings of cyber sickness by the virtual learning environment four times, which is 18.2% of the total reported counted codes for their treatment. Feelings of cyber sickness covers topics of nausea, stomach pain, head pain, light headiness, and psychological uneasiness with feeling a difference between what the body parts are doing and what the mind thinks the body parts are doing. Treatment group participants did not express cyber sickness comments. Control group participants expressed being nauseous, having cyber sickness, feeling disconnected from body movement to their mental models, and that their brain felt like things were not cooperating right.

5.5 Discussion

5.5.1 Interpretation of Learning Assessment

The control and treatment group participants showed no measurable difference between their pre-assessment learning scores, implying that they started the experiment with the same level of knowledge on the “bubble sort” algorithm. Both groups had a median score close to one on their pre-assessment learning score, which indicated low pre-existing knowledge, since the assessment is four questions long. After the treatments, the participants from both groups showed statistically higher post-assessment learning scores compared to their pre-assessment learning scores. This suggests that both treatments were effective virtual learning environments. However, there was a statistically significant difference between the groups’ post-assessment

learning scores, meaning that the treatment group participants learned the “bubble sort” algorithm better than the control group participants.

The results of the learning assessments showed that the participants from both groups learned the “bubble sort” algorithm through the virtual learning environment and that the treatment group learned better than the control group. This suggests that the virtual learning environment could be used as alternative teaching tools in CS education, supplementing traditional teaching methods and possibly enabling new learning methods for students in the classroom and at home. The results also suggest that the more natural that an environmental traversal interaction is, i.e., a stronger kinematic symmetry, the learner will have better comprehension of the material. There were no statistical differences in the retention of the knowledge between the two environmental traversal interactions.

5.5.2 Interpretation of Task Time Assessment

Participants in both groups had similar total session times of completing the six learning tasks in the virtual learning environment. Of the six tasks, the treatment group had a statistically faster task time for tasks 1 and 2 compared to the control group. Although the treatment group had a mean over a minute faster for the total session time over a minute compared to the control group, the only statistically faster task times for the treatment group was in the first two tasks.

This was possibly due to fact that the lists in the earlier tasks were shorter creating less distance to travel and giving an advantage to the treatment group that diminished as the later lists got longer creating larger distances to travel. Although the last task, which had the largest distance to travel, still showed the treatment group performing the task faster than the control group. There may be a distance where the control group does start to outperform the natural walking group, but

within the current limitations of standalone VR headsets and normal room sizes, the natural walking treatment did show a faster task time completion time.

5.5.3 Interpretation of Usability Assessment

Data analysis of the simulator sickness survey and the attention, presence, and spatial awareness sections of the usability survey did not reveal any interesting trends. Overall, both groups reported low scores on a seven point Likert-type scale for simulator sickness, and high scores for all sections of the usability survey. One question within the usability section of the usability survey showed a statistical difference between the groups, which happened to ask about movement enjoyment. The treatment group statistically enjoyed the amount of body movement and kinematic symmetry available to them while learning with this environmental traversal interaction. Analysis of the open-ended responses revealed four major codes to report on: embodied interaction enjoyment, embodied interaction improvement, embodied cognition enjoyment, and cyber sickness (see Figure 5.10).

Treatment group participants reported enjoyment or positive feelings toward the embodied interaction experiences of the virtual learning environment at the same level to the control group participants. Treatment group participants reported improvement suggestions or negative feelings toward the embodied interaction experiences of the virtual learning environment at near same level, to the control group participants. Treatment group participants reported enjoyment or positive feelings toward the embodied cognitive experiences of the virtual learning environment at a much higher level to the control group participants. This is a large difference in the enjoyment towards the embodied cognitive experience and shows that the treatment group participants had strong positive emotions toward embodied learning and this is reflected in their statistical difference in reporting high levels of “How much did you enjoy moving your body while learning”.

Treatment group participants reported feelings of cyber sickness by the virtual learning environment at a much lower level to the control group participants. Interesting, the simulator sickness survey did not show the level of cyber sickness reported from the control group participants. It could be that the simulator sickness was the last survey given and the participants were tired at that point, which is why most answers on the simulator sickness survey were reported at the one point of the seven-point Likert-type scale. In either case, the control group reported a modest level of cyber sickness symptoms that contributed to their statistical difference in reporting low levels of “How much did you enjoy moving your body while learning”.

5.5.4 Study Limitations

Experimental bias existed and could not be reduced from the influence that all participants were already registered as undergraduate computing students at a technical higher educational institution. Both conditions taught the participants to “bubble sort” lists up to eight elements and learning assessments tested “bubble sort” algorithm up to six elements. Further training sessions and assessments may need lists with more elements to verify educational efficacy of both conditions.

5.6 Conclusion

This chapter explored the effect of varying the kinematic style of traversal within an immersive virtual learning environment on user performance. The two kinematic styles of traversal that were compared are natural walking and hand controller-based walking. The traversal methods and their effects were explored on undergraduate CS students learning a fundamental CS sorting algorithm called “bubble sort”, which is an important computational skill for CS learners. User testing confirmed that the treatment group that learned to “bubble sort” a list using the natural walking kinematic style of environmental traversal showed statistical improvements

in learning, usability, and task time compared to the control group that used the hand-controller kinematic style of environment traversal.

This showed that the kinematic style of environmental traversal should be taken into consideration as alternative teaching tools in STEM education when designing AR/VR educational experiences. Students that find educational topics within the STEM fields difficult to learn, may find alternative teaching methods useful to maximize their performance and comprehension. When designing AR/VR educational tools, having the user move through and interact with the virtual environment may help learners engage with difficult to learn STEM concepts, and attract a more diverse population to the STEM fields.

CHAPTER 6

CONCLUSION

6.1 Summary of Key Findings

The emerging technologies of AR/VR may have vast implications to societal communication and representation of information. AR/VR computer interfaces are unique in that they may be placed spatially in 3D around the user. This affords new methods of presenting information to the user and user interactions with that information. As demonstrated, these spatial interactions of AR/VR computer interfaces may enhance the efficacy of virtual learning environments beyond what is currently possible with monitor-based computer interfaces.

This may be especially impactful in the education of STEM professionals. Prior research has shown that simulations and visualizations improve the performance and engagement of STEM learners compared to live instruction and textbook reading. To build upon this research, this dissertation examines how user traversal across spatial AR/VR computer interfaces impacts their learning performance. The goal is to help understand the benefits of AR/VR computer interfaces for the education of STEM professionals. For educational technology research, it is important to build off prior research in both the learning science and HCI fields.

Examining AR/VR's impact on STEM education through the fields of learning science, and HCI allow for unique understanding of how these emerging technologies will impact our knowledge-based society. Identifying STEM educational use cases of AR/VR may help scope research efforts, and improve technology efficacy, since there is a lack of research into AR/VR as a learning environment for widespread educational applications [13]. To address this research gap, this dissertation

examined a fundamental AR/VR interface capability, the ability to traverse a virtual environment, and its impact on learning.

The first study of the dissertation compared the performance of STEM learners within a physical and a virtual learning environment, both with no traversal abilities. Learners in the physical environment were seated during their learning experience. Learners in the virtual environment had their entire AR/VR interface within reaching distance of their seated position. Evidence from this study suggests that instructional delivery in a virtual environment with no traversal of the spatial AR/VR interface offers comparable learning efficacy to the traditional physical environment.

The second study of the dissertation compared the performance of STEM learners seated in a physical environment against STEM learners in a virtual environment that required them to traverse the spatial AR/VR interface. Evidence from this study suggests that instructional delivery in a virtual environment with required traversal of the AR/VR interface offers comparable learning experiences to the physical equivalent. Additionally, the evidence suggests that AR/VR interfaces with environmental traversal interactions can offer high user engagement as an effective supplement to traditional physical learning environments.

The final study of the dissertation compared the performance of STEM learners using the same virtual learning environment, but alters the environmental traversal ability between the two groups. It compared the efficacy of a natural walking traversal method to a hand controller-based traversal method on learning performance of the subjects. Evidence from this study suggests that the more embodied traversal interaction of natural walking offers better learning, retention, usability, and task time performance to its users.

The first and second studies of the dissertation showed that AR/VR computer interfaces, both with and without user traversal ability, offer capable learning efficacy to their physical environmental equivalents and can offer higher engagement, increased

learning metrics, and enable alternative learning methods. Once it was shown that AR/VR computer interfaces, both with and without user traversal, can have comparable efficacy to traditional learning methods, the third study looked at how altering the user traversal ability on the same AR/VR computer interfaces impacted its learning efficacy. It was shown that the more embodied traversal of natural walking across a spatial AR/VR interface may have strong impact on the technology's learning efficacy. This dissertation offers evidence that AR/VR technologies, with and without user traversal, are suitable STEM learning environments. Additionally, providing higher levels of traversal capabilities may increase learning performance.

6.2 Contribution of Work

- Identified new connections involving embodiment theories in literature between learning and HCI science.
- Designed new interaction techniques based on embodiment theories for virtual learning environments [78].
- Developed and released new LC curriculum for virtual learning environments [79].
- Developed and released new CS educational software for VR systems [81].
- Identified novel benefits for socialization within virtual learning environments [80].
- Identified novel benefits for interaction techniques for learner performance within virtual learning environments [82].
- Identified novel benefits of virtual learning environments to secondary and collegiate STEM students. [70].

The contribution of this body of work to the fields of learning science and glshci involved novel benefits to users of virtual learning environments along with novel study methodologies and literature review. Novel benefits of virtual learning environments included reduced barriers to successful socialization. The virtual treatment participants from the first study reported that VR can address the anxiety of freshman relating to their new college environment full of strangers that may carry

risk of public humiliation. The participants indicated that socializing in VR helped remove the fear from public interactions with unknown fellow students.

We identified new connections involving embodiment theories in literature between learning and HCI science. New theories in learning science involve ideas of embodied cognition, while HCI studies are starting to explore ideas of embodied interaction. This guided our design efforts of new interaction techniques based on embodiment theories for virtual learning environments. The software used in the second and third study had the user interactions centered the learning of binary counting and “bubble sort” algorithm around user movement of their arms and legs. The overall impression received from observing the participants in the second study was that CSpresso, even in its preliminary state, was engaging and fun. Students made full use of the Quest’s untethered feature, breaking out into victory dances and freely moving about in their 20 by 20 foot space (see Figures in Appendix H and I). The third study recorded stronger evidence for the efficacy of the embodied interactions by indicating statistical differences in the participants learning, and time to complete tasks between the partial traversal of hand controller walking and full traversal of natural walking.

6.3 Future Direction

For future studies based on the virtual collaboration study, see Chapter 3, the research would focus on combining collaboration research with learning science research, particularly for undergraduate computer science education where group-based problem solving and communication skills are essential for students upon entering the job market.

For future studies based on the binary counting study, see Chapter 4, the research would look at the student’s recall of the lesson learned over a period of time. It is believed this is where a significant difference between a standard lesson

and hands-on VR technology will be seen. The second level of CSpresso has already been designed, which teaches bubble sort, a CS sorting algorithm. An AR alternative teaching tool has also been developed for the binary counting concept that works with a textbook supplemental section designed to work with the AR educational experience. The researchers would like to test both educational experiences on the same student demographic, and are currently testing the VR binary counting activity with different virtual environment features to see the effects on undergraduate students.

For future studies based on the bubble sort study, see Chapter 5, the study methodology would be revised to administer the retention assessments in a lab setting as opposed to a remote setting to verify reasons for retention assessments showing little to no loss of knowledge compared to the post assessment, which would be expected. In order to get a richer analysis of the learning processes per condition, the researchers proposed recording the participants steps in all learning assessments to analyze another level of detail, including the time to complete assessments, and the error rate of the algorithm steps.

6.4 Final Remarks

In summary, this dissertation presented several examples of AR/VR educational technology studies involving learners from primary and undergraduate STEM education. Each study found interesting learning and usability considerations while examining different STEM topics with different kinematic symmetries of environmental traversal. This led to a final identification of the learning and usability impacts of the kinematic symmetry of environmental traversal for one STEM learning task. Further studies will need to investigate a higher fidelity of kinematic symmetries of environmental traversal and across a larger spectrum of learning topics to generalize the knowledge

gained in this dissertation to the broader applications of AR/VR to the HCI and educational technology fields.

APPENDIX A

ACADEMIC ASSESSMENT

In this appendix, you will find a description of the common core exam academic metric assessment used in the collaboration training study of chapter three.

Instructions: For each month of the Fall 2018 semester, please fill out this survey. We ask you to fill out what you think your grade will be for the following week's exam in each common core class that you are taking. Please use the letter grading system (A, B+, B, C+, C, D, F).

Date: _____ Semester Week Number: _____
Subject Number: _____

Common Core Class Name: _____
Subject: _____ Course Number: _____ Section Number: _____

What grade do you think you will receive for next week's exam: _____

Common Core Class Name: _____
Subject: _____ Course Number: _____ Section Number: _____

What grade do you think you will receive for next week's exam: _____

Common Core Class Name: _____
Subject: _____ Course Number: _____ Section Number: _____

What grade do you think you will receive for next week's exam: _____

Figure A.1 Common core exam academic assessment.

APPENDIX B

SOCIAL ASSESSMENT

In this appendix, you will find a description of the weekly social metric assessment used in the collaboration training study of chapter three.

Instructions: For each week of the Fall 2018 semester, please fill out this survey. We ask you to fill out a section of this survey for each common core class that you are taking. For each common core class, we ask you to enter the full names of up to ten NJIT freshman undergraduate students that helped you in this class, and up to ten students that you helped. Help is defined as over 5 minutes of direct tutoring instruction focused on material from that common core class. If listing the same person in later weeks, please write their name in the same way as previous weeks (e.g., If you listed "Mike Jordan", please continue to use that name instead of "Michael Jordan", "Mick Jordan", etc.).

Date: _____ Semester Week Number: _____
Subject Number: _____

Common Core Class Name: _____
Subject: _____ Course Number: _____ Section Number: _____

List up to eight (8) students who helped you this week:

First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____

List up to eight (8) students you helped this week:

First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____
First Name: _____	Last Name: _____

Figure B.1 Weekly social metric assessment.

APPENDIX C

BINARY COUNTING LEARNING ASSESSMENT

In this appendix, you will find a description of the learning assessment used in the binary counting study of chapter four. It was used as a pre and post assessment.

Question 1

The "binary number" system uses **zero** and **one** to represent whether a card is face-up or not. **0** means the card is hidden, and **1** means you can see the dots. The total number of dots is the "decimal number." So, you can figure out the "decimal number" by adding up all the dots from the face-up, or **1**, cards that you can see. For example:



*The left example is 101. That equals the decimal number 5.
The right example is 10101. That equals the decimal number 21.*

- A. Can you work out what the binary number 100 is as a decimal number?: _____
 B. Can you work out what the binary number 11111 is as a decimal number?: _____

For binary numbers, we use zero and one for convenience. They can actually be any two distinct symbols. For example, other ways we typically label binary numbers are:

0 can also be off or false, 1 can also be on or true

So the example you saw earlier, 01001 can also be written as:

01001 = off on off off on
 01001 = false true false false true

Knowing that you can use **any** two symbols to represent **zero** and **one**, can you work out the following coded numbers?

 (😊=1 😞=0)	=	 (👦=1 👧=0)	=
 (⬆️=1 ⬇️=0)	=	 (+ =1 - =0)	=
 (👍=1 👎=0)	=	 (👕=1 👚=0)	=
 (☀️=1 🌙=0)	=	 (🚗=1 ✈️=0)	=
 (✅=1 ❌=0)	=	 (♠️=1 ♣️=0)	=

Figure C.1 Binary counting learning assessment.

APPENDIX D

DEMOGRAPHIC ASSESSMENT

In this appendix, you will find a description of the demographic assessment used in the bubble sort study of chapter five. It was used as a pre assessment.

1. Please indicate your gender: Male Female Other
2. Please indicate your age: _____
3. What is your country of origin? _____
5. What is your native language or languages (column 1)?
 - At what age did you begin to learn each (column 2)?
 - In a typical day, which languages do you use at what percent (column 3)?
 - Rate your skill with 1 being Excellent and 7 not at all (columns 4-6)

Language	Age acquired	% used a day	Read	Speak	Write

13. How often do you use a video game system (at home/work/school/ arcade)?
 Never Once a month 1-4 times a month
 5-10 times a month 11-20 times a month More than 20 times a month
14. What types of games do you play? (Check all that apply)
 Action Adventure Simulation Sports Strategy/Puzzle
15. How often do you use a Virtual Reality technology?
 Not at all Moderately Frequently
 Can you please offer some details? _____
16. How often do you use Augmented Reality technology?
 Not at all Moderately Frequently
 Can you please offer some details? _____
17. How familiar are you with VR devices?
 Not at all 1 2 3 4 5 6 7 Very well
18. How familiar are you with AR devices?
 Not at all 1 2 3 4 5 6 7 Very well
19. Have you eaten prior to the experiment? No Yes, When? _____
20. Do you wear corrective lenses? No Yes, Type: _____ Number? _____

Figure D.1 Demographic assessment.

APPENDIX E

BUBBLE SORT LEARNING ASSESSMENT

In this appendix, you will find a description of the learning assessment used in the bubble sort study of chapter five. It was used as a pre, post, and retention assessment.

What are the correct intermediate steps of the following data set when it is being sorted with the bubble sort? 8, 5, 2 *

5, 2, 8 -- 2, 5, 8

5, 8, 2 -- 5, 2, 8 -- 2, 5, 8

5, 8, 2 -- 2, 5, 8

8, 2, 5 -- 2, 8, 5 -- 2, 5, 8

What are the correct intermediate steps of the following data set when it is being sorted with the bubble sort? 15, 20, 10, 18 *

15, 10, 20, 18 -- 15, 10, 18, 20 -- 10, 15, 18, 20

10, 20, 15, 18 -- 10, 15, 20, 18 -- 10, 15, 18, 20

15, 20, 10, 18 -- 15, 10, 20, 18 -- 10, 15, 20, 18 -- 10, 15, 18, 20

15, 18, 10, 20 -- 10, 18, 15, 20 -- 10, 15, 18, 20 -- 10, 15, 18, 20

What are the correct intermediate steps of the following data set when it is being sorted with the bubble sort? 5, 11, 2, 14, 8 *

5, 2, 11, 14, 8 -- 5, 2, 11, 8, 14 -- 5, 2, 8, 11, 14 -- 2, 5, 8, 11, 14

5, 2, 11, 14, 8 -- 2, 5, 11, 14, 8 -- 2, 5, 11, 8, 14 -- 2, 5, 8, 11, 14

5, 11, 2, 8, 14 -- 5, 2, 11, 8, 14 -- 5, 2, 8, 11, 14 -- 2, 5, 8, 11, 14

5, 2, 11, 14, 8 -- 5, 2, 11, 8, 14 -- 2, 5, 11, 8, 14 -- 2, 5, 8, 11, 14

What are the correct intermediate steps of the following data set when it is being sorted with the bubble sort? 5, 8, 2, 11, 6, 4 *

5, 2, 8, 11, 6, 4 -- 5, 2, 8, 6, 11, 4 -- 5, 2, 8, 6, 4, 11 -- 2, 5, 8, 6, 4, 11 -- 2, 5, 6, 8, 4, 11 -- 2, 5, 6, 4, 8, 11 -- 2, 5, 4, 6, 8, 11 -- 2, 4, 5, 6, 8, 11

5, 2, 8, 11, 6, 4 -- 5, 2, 8, 6, 11, 4 -- 5, 2, 8, 6, 4, 11 -- 5, 2, 8, 4, 6, 11 -- 2, 5, 8, 4, 6, 11 -- 2, 5, 4, 8, 6, 11 -- 2, 5, 4, 6, 8, 11 -- 2, 4, 5, 6, 8, 11

5, 2, 8, 11, 6, 4 -- 5, 2, 8, 6, 11, 4 -- 2, 5, 8, 6, 11, 4 -- 2, 5, 6, 8, 11, 4 -- 2, 5, 6, 8, 4, 11 -- 2, 5, 6, 4, 8, 11 -- 2, 5, 4, 6, 8, 11 -- 2, 4, 5, 6, 8, 11

5, 2, 8, 11, 6, 4 -- 5, 2, 8, 6, 4, 11 -- 5, 2, 8, 4, 6, 11 -- 5, 2, 4, 8, 6, 11 -- 5, 2, 4, 6, 8, 11 -- 2, 5, 4, 6, 8, 11 -- 2, 4, 5, 6, 8, 11

Figure E.1 Bubble sort learning assessment.

APPENDIX F

SIMULATOR SICKNESS ASSESSMENT

In this appendix, you will find a description of the simulator sickness assessment used in the bubble sort study of chapter five. It was used as a post assessment.

<u>SYMPTOMS</u>	<u>RATING</u>			
1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eyestrain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increased	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. Dizziness with eyes open	None	Slight	Moderate	Severe
11. Dizziness with eyes closed	None	Slight	Moderate	Severe
12. Vertigo	None	Slight	Moderate	Severe
13. "Fullness of the head"	None	Slight	Moderate	Severe
14. Stomach awareness	None	Slight	Moderate	Severe
15. Burping	None	Slight	Moderate	Severe

Figure F.1 Simulator sickness assessment.

APPENDIX G

USABILITY ASSESSMENT

In this appendix, you will find a description of the usability assessment used in the bubble sort study of chapter five. It was used as a post assessment.

1. Please rate, how easy was it to learn and understand the material presented?
Very difficult 1 2 3 4 5 6 7 Very easy
2. Please rate, how much did you enjoy the learning experience?
Not at all 1 2 3 4 5 6 7 Very much
3. Please rate, how much would you like to use this experience in your CS class?
Not at all 1 2 3 4 5 6 7 Very much
4. Please rate, how much did you enjoy using the interface?
Not at all 1 2 3 4 5 6 7 Very much
5. Please rate, how much did you enjoy moving your body while learning?
Not at all 1 2 3 4 5 6 7 Very much
6. Please rate, how much did the interface help you with the learning tasks?
Not at all 1 2 3 4 5 6 7 Very much
7. Please rate, how quickly were you are to complete the learning tasks?
slow 1 2 3 4 5 6 7 fast
8. Please rate, how comfortable was your experience with the application?
Not at all 1 2 3 4 5 6 7 Very much

Figure G.1 Usability assessment.

APPENDIX H

SOFTWARE DESIGN - MAKING OF CSPRESSO

In this appendix, you will find the first of two books explaining the design of the software used in the binary counting study in chapter four. The basis of that software design was also used to build the software used in the bubble sort study in chapter five. The software design description excerpts are from “Making of” books that were presented at the Oculus Connect 6 Conference on September 25-26, 2019 at the San Jose McEnery Convention Center in San Jose, California USA.

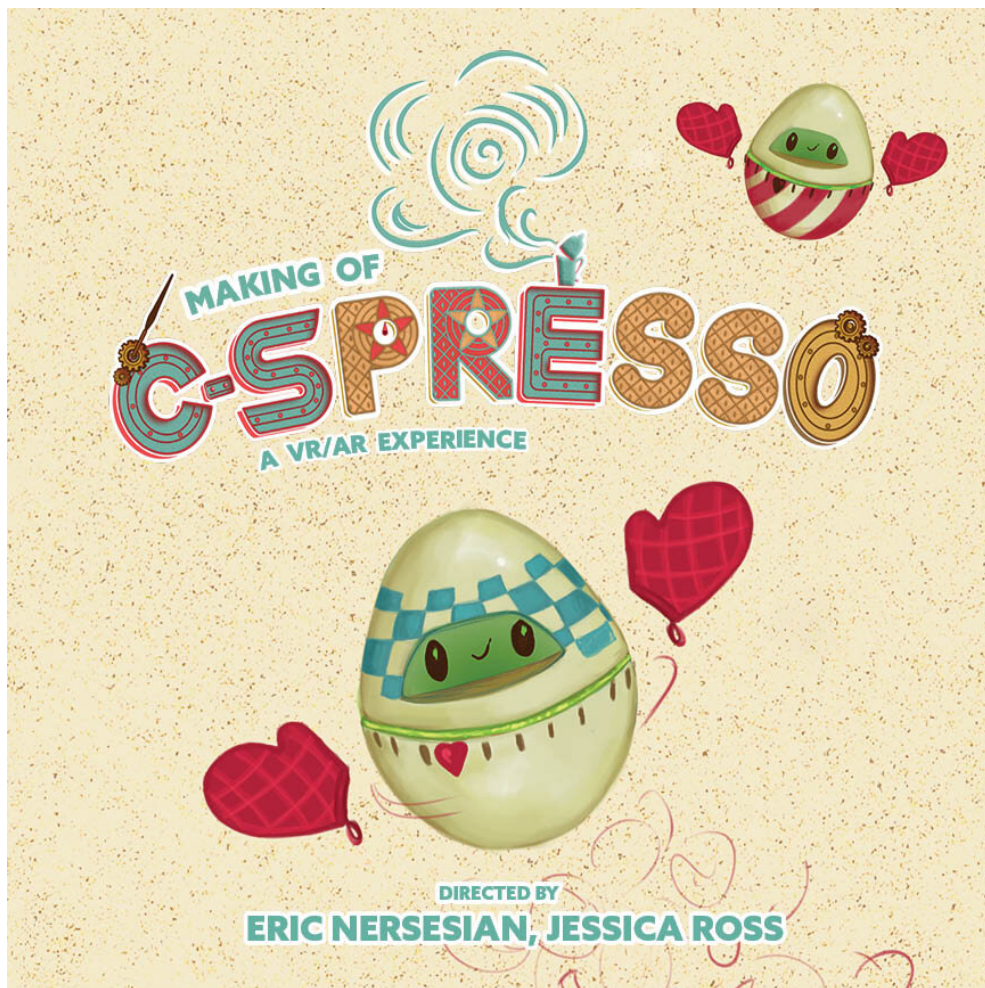
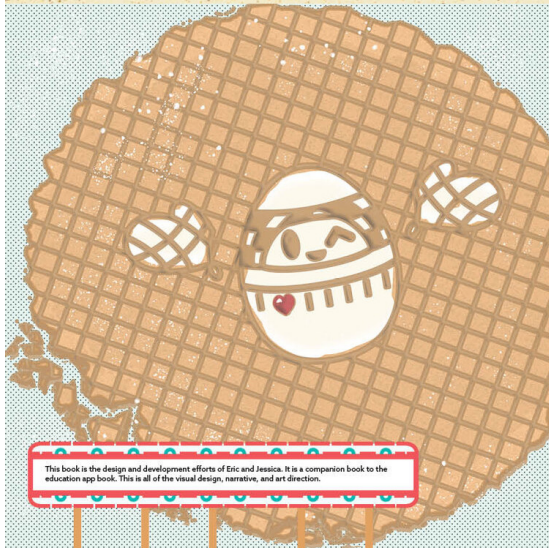


Figure H.1 Making of CSpresso cover page.



The Making of C-Spresso

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CHAPTER TWO
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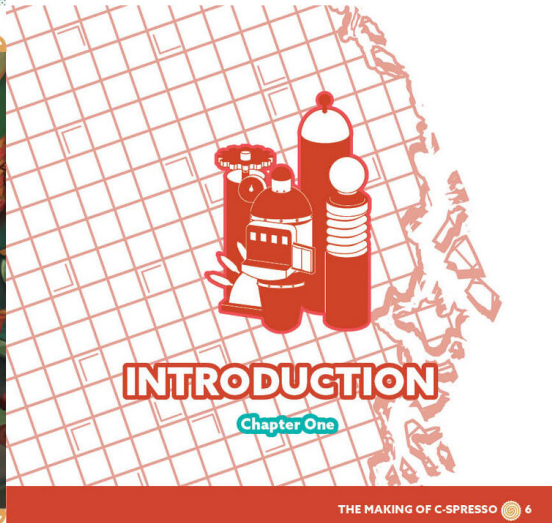
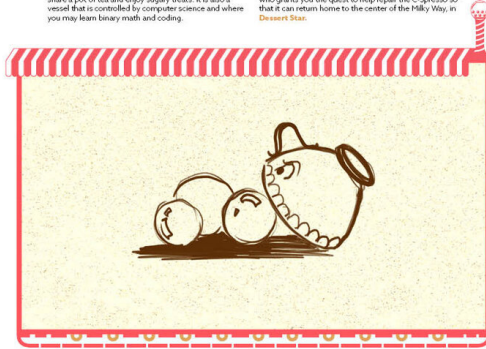


Figure H.2 Making of CSpresso pages 1-6.

Introduction

The world of C-Spresso is one made up of 75 and 0% candy, tea, coffee, magic, and space travel. It resides right in the center of the Milky Way, where inhabitants from all over the galaxy come together to share a pot of tea and enjoy sugary treats. It is also a vessel that is controlled by computer science and where you may learn brain math and coding.

In this immersive experience, you find yourself inside a spaceship that has been damaged during an intergalactic space storm. Here, you'll meet the ship's assistant, Eggbert (but you may call him Egg), a little egg timer who grants you the quest to help repair the C-Spresso so that it can return home to the center of the Milky Way, in Dessert Star.



THE MAKING OF C-SPRESSO 7

Story

All sweetness in the galaxy comes from one secret location, smack dab in the center of our Milky Way. If you are ever lucky enough to make it there, you will realize that the very air you breathe tastes like the inside of a bakery or maybe a candy store. At that point in your journey, you will know that you are approaching the hidden city of Dessert Star. If you've ever wondered where the very concept of sweets and treats originated, it is here. The atmosphere of Dessert Star is completely sweet, from fruits to candy, and even flowers.

The C-Spresso is Dessert Star's most iconic and significant space station. Here, all of the galaxy's sweet treats and confectionery delights are manufactured and distributed to all inhabitants within the Milky Way. This helps keep the peace within the galaxy, keeping everyone happy and peaceful, with sugary treats, nice hot coffees, and even tea time, especially tea time. All within the galaxy live coming to the city of Dessert Star, to unwind from a hectic work day, or to share a pot of tea with other nearby, intergalactic friends. While Earth is within the Milky Way, it is just too far away to visit in time for brunch or tea time, so the C-Spresso makes its rounds along the

Milky Way, doing air drops of coffee beans, sugar cane seeds, and tea leaf plants for the little Earthlings to harvest and distribute among themselves. The next time you find yourself enjoying a candy cane, licorice, or hot cocoa, you could appreciate this magical place far away in the center of the Milky Way, that is rumored to taste like happiness, and you will know why!

It has been this way for centuries, and has kept all within the galaxy happy and full of cheery energy. Unfortunately for them, an asteroid has just torn right through the center of the Milky Way, splitting the docking station where the C-Spresso recharges between rounds and hurling it far off into space. The inhabitants of the galaxy have since been in a frenzy, trying to locate the ship and bring it back to Dessert Star.

Someone brave will have to go out into theinky blackness outside the Milky Way, find the C-Spresso, and bring her back to Dessert Star, so that everyone's lives can go back to normal. Until then, the inhabitants of the Milky Way will be dreaming about when their ship will be back so they can warm up, after a much too long period without delightful hot beverages or sweets!



JESSICA ROSS

NOTE FROM THE VISUAL DESIGNER

Growing up, my brothers and I would find that we did not learn like everyone else. As the oldest of 3 children with ADD, my parents would learn the importance of a school system willing to accommodate children of all different learning styles. Keeping up with fellow classmates was difficult, especially in math and science. The only time I found ways when we had to do something creative and (coincidentally enough), the only time I learned anything was when it was presented to me in a creative way. Educational games and immersive experiences lend themselves to people like my brothers and me—people who can learn just not in the same way as the majority of their classmates. People who process information differently, retain information differently, and do things differently have been an inspiration for projects like C-Spresso and other educational games. It is no secret that the process of learning varies from individual to individual; some students are spatial learners while others are auditory learners, some students need to be active and use their hands while learning something. It is because of this reality that other means of education are crucial so that no individual is excluded from learning and doing well in their academic careers.

Often when a child is presented information in an engaging way, they are more able to retain that information, focus, and as a result, learning becomes a positive experience, rather than one filled with stress and disappointment. For this reason, creating educational experiences that immerse the user is at the core of our objective, within HROU Lab. If we are successful, there will be less children excluded from the potential to thrive in their learning and more children who are not only enthusiastic about learning, but confident in their potential to learn.

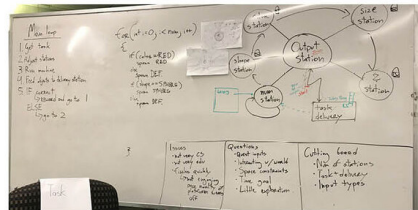
C-Spresso is a project comprised of education, outreach, computer science, and immersive storytelling. Professionals from many different backgrounds were recruited throughout development, including researchers, educators, game developers, UI/UX designers, artists, industrial designers and story artists. Every design decision was examined and adjusted as needed, to be sure that the user would get the most out of every interaction throughout the experience. It is a project that truly shows how important collaboration is between schools of thought, especially when putting together something like an immersive educational experience.

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Prototyping & Designing for VR

Designing for VR is a challenge in itself, since it is a relatively new medium for gaming or education. In telling any type of narrative in VR, designers must find a way to direct the user in the desired direction and point within the 360 environment to focus on, or else risk losing the user's attention and resulting in a frustrating, confusing experience. This combined with our main objective of teaching a complex topic like Computer Science, made for a very intimidating project. We would need the help of experts in not only computer science, but in how to reach it effectively within the middle school age group. We would also need advisement on topics such as learning science, learning styles, and lesson plan design.

With the help of CS education professionals, Dr. Margyta Vrolikova and Dr. Michael Lee, collaborated with the design team to craft a framework for the game play and interactions. UI/UX design followed and soon we were whiteboarding interactions, game mechanic ideas, and how to use these to tie in and reinforce the learning objectives. The lessons would be simple, with minimal interactions to reduce what is referred to in UX design as cognitive load. This refers to giving the user (or player) too many things to remember, to successfully complete an interaction. Since we are also teaching the user about computer science, we had to be extra careful when designing the game mechanics and interactions.



THE MAKING OF C-SPRESSO 11



Inspiration

In preparation for developing this experience, we did research into the demographic we were designing for: grades 5-12, male and female. We researched highest grossing films, games, and series within children's entertainment. After spending time gathering notes on what titles drew the most interest from all gender groups, we began to find a thread of commonality to start following. Game titles such as *Fortnite*, *Minecraft*, *Angry Birds*, *Tron: Evolution*, and *Zelda* shared similar color palettes of bright greens, yellows, and oranges. Shapes were large, simple, and rounded in form (with the exception of which was more sophisticated in visuals with more realistic forms), and the overall atmosphere within each world was cheerful, with light-hearted music. After researching film and series titles that appealed to many different demographics, we first were interested in titles that had a timeless quality—a story that did not fade with time but still draws the attention of new generations. Some of these titles were *Willy Wonka's Chocolate Factory*, *Alice in Wonderland*, *The Wizard of Oz*, and *Dr. Seuss* stories—all have this whimsical element that seems to leave a lasting impression and fondness with their audience. As artists, designers, and storytellers, we wanted to create an experience that was designed with these influential titles and stories as core inspiration.

INTRODUCTION: PRETEXT 10

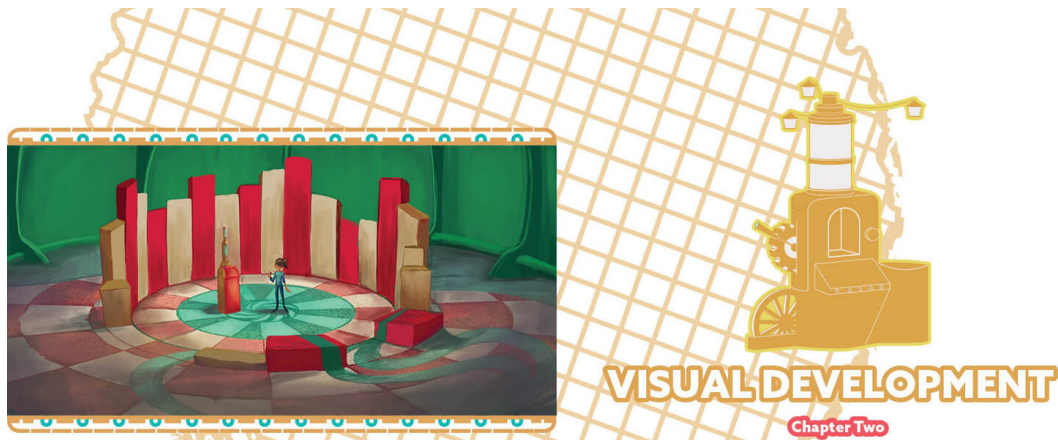


White Board Prototyping, Adam Spryzynski

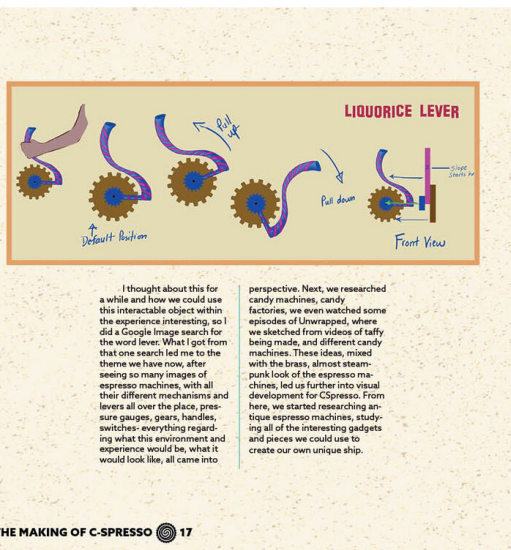
During the prototyping phase, Adam had us arrange a few areas of the room with computer chairs, small filing cabinets, bulletin boards (any junk we could find around the studio), and arrange it all into one big circle; this would represent one full interaction loop that the user would go through to complete one task. As the prototyping began taking form, we realized that the experience of going from one area to another, while pulling levers or pressing buttons, started to feel like what you may experience if you were in some kind of ship or factory.

INTRODUCTION: PRETEXT 12

Figure H.3 Making of CSpresso pages 7-12.



Start of Visual Development



I thought about this for a while and how we could use this interactive object within the experience interesting, so I did a Google image search for the word lever. What I got from that one search led me to the theme we have now, after seeing so many images of espresso machines, with all their different mechanisms and levers all over the place, pressure gauges, gears, handles, switches- everything regarding what this environment and experience would be, what it would look like, all came into

perspective. Next, we researched candy machines, candy factories, we even watched some episodes of Unwrapped, where we sketched from videos of taffy being made, and different candy machines. These ideas, mixed with the brass, almost steam-punk look of the espresso machines, led us further into visual development for C-Spresso. From here, we started researching antique espresso machines, studying all of the interesting gadgets and pieces we could use to create our own unique ship.

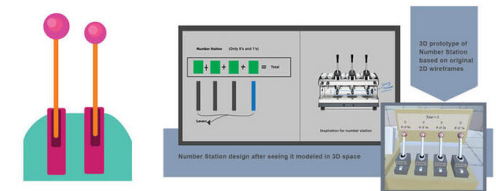
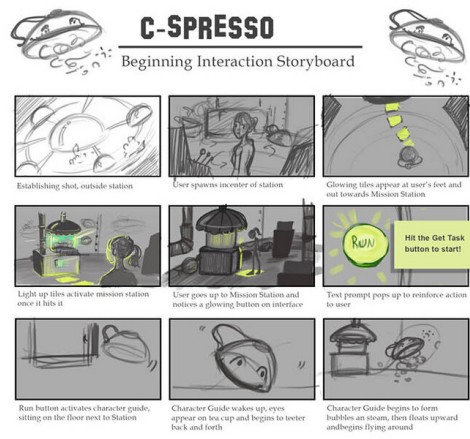


Figure H.4 Making of CSpresso pages 13-18.



Designing Eggbert

It might go without saying, that we had a great time building this world and creating these zany, whimsical machines and assets. One of the most fun parts in this production was designing Eggy, our little guide. We needed to keep the design very simple with little animation, yet still have an interesting character. I started drawing little beacup creatures and Brent Hartwell (Industrial Design Student) simplified the design further with the idea of a little egg timer. The rest of the team, designers, programmers, and researchers, were excited about this little egg timer character and once that was decided, Eggy was brought into the world of C-Spresso.

In designing for VR, everything becomes a little more complicated due to the fact that it is a relatively new medium and the design is not restrained to a 2D surface like a tablet or desktop monitor. Even the UI (user interface) of the experience needs to feel easily accessible and understandable within the 3D environment. For this reason, we designed the experience so that the user would interact with as few 2D interfaces as possible. Eggy would be serving as not only a guide, but as a "start" button, for the beginning of the

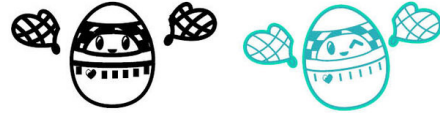
experience, when the user would be prompted to give him a high-five, when ready to begin.

Originally, Eggy had no hands or arms (because he's an egg timer), and the user would have to tap his head to begin, but after testing this in the Quest, researcher Dr. Vireničová pointed out that the interaction felt odd because the only way to interact with Eggy was to touch anywhere on his head or face. She pointed out that with anthropomorphic characters, users expect to see and interact with hands and arms.

After brainstorming on how to tackle this within the time constraints, Brent said, "How about oven mitts?"

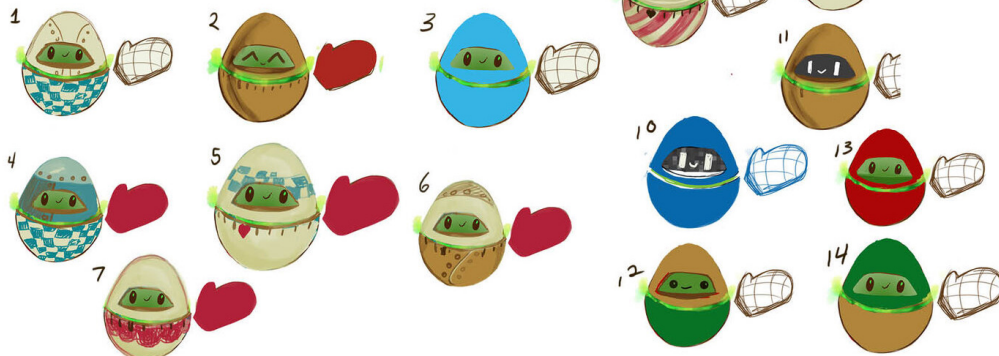
And that was that!

"How about oven mitts?"



VISUAL DEVELOPMENT 20

Eggy (Eggbert) Concepts



THE MAKING OF C-SPRESSO 21

VISUAL DEVELOPMENT 22



"We decided we needed a friendly presence in the space, an assistant of sorts for both younger people who we would be catering this towards and adults alike. So that's when I came up with the idea of associating a common image with the kitchen: an Egg timer. Eggy is the first thing you see when users are spawned into the space and reached you how to operate the game. He is a friendly little being that is simply designed to always be there for you, I had it in mind that he could be excitable yet

- Brent Hartwell

shy. I wanted him to be able to express those emotions so a screen was made for his eyes which vary between what the user does, his little hand oven mitts do the same to help the user relate and interact with our Eggy. He stays with you the entire time reminding the user of their objective in his speech bubble objective, which needed to be seen across the room for users and is always there to encourage the user."

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Figure H.5 Making of CSpresso pages 19-24.

Sugar Goblins



In the next phase of design, we have many different characters to play and interact with, which we really look forward to bringing to life. Some of these characters include the teacup creatures which the user creates by stacking one teacup on top of another and then my favorite, the sugar goblins. In the world of C-Spresso, these little creatures live off of the chemical, ethyl formate, which is the very chemical that gives raspberries their flavor and the Milky Way, that trademark scent!

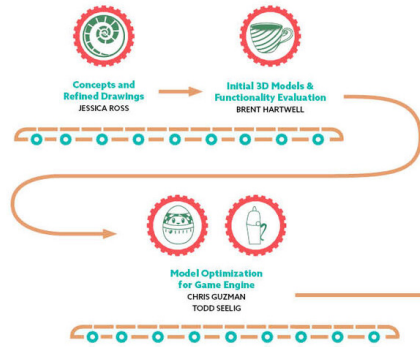
THE MAKING OF C-SPRESSO 25

Sugar Goblins & Teacup Monsters



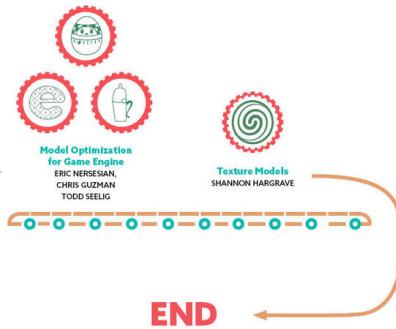
VISUAL DEVELOPMENT 26

Asset Pipeline



THE MAKING OF C-SPRESSO 27

Asset Pipeline



VISUAL DEVELOPMENT 28

Oculus Connect 6



Color sketch of proposed kiosk display at future demo sessions. Here, all of the content created around C-Spresso (AR & VR apps, painting app on Facebook Portal, and C-Spresso books), are displayed here.

THE MAKING OF C-SPRESSO 29

Additional Concepts



VISUAL DEVELOPMENT 30

Figure H.6 Making of CSpresso pages 25-30.

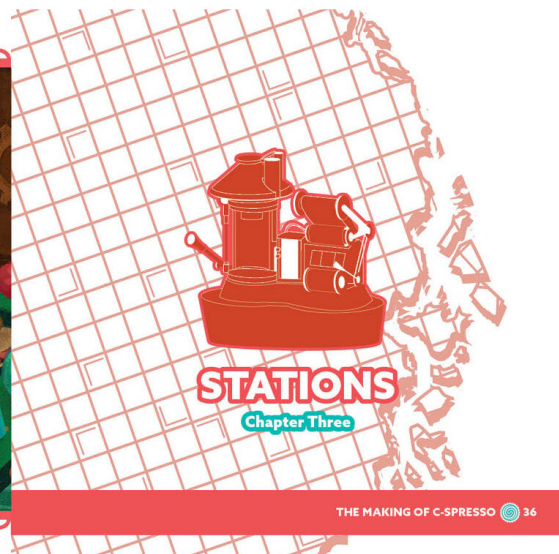
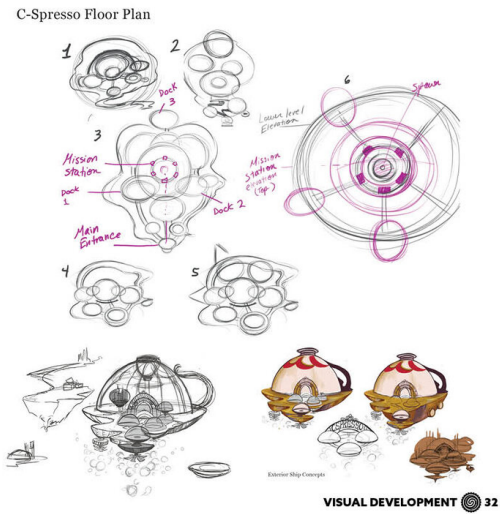
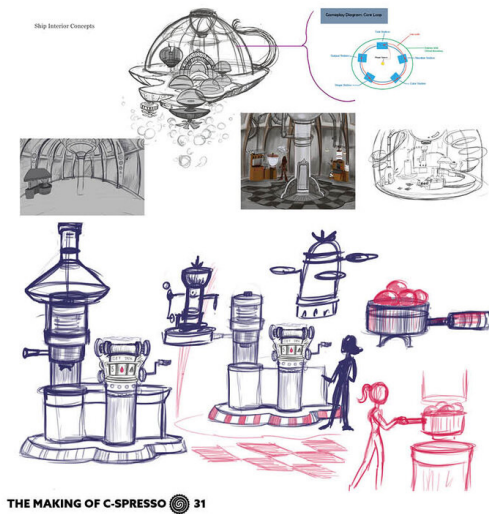
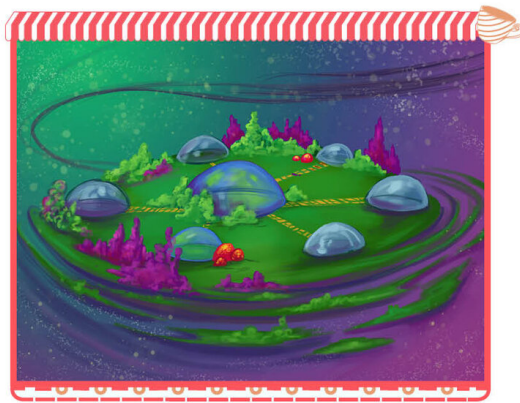


Figure H.7 Making of CSpresso pages 31-36.

The Stations



THE MAKING OF C-SPRESSO 37



The original idea for CSpresso was that it would be the center of an intergalactic city, where all of the stations would be in their own enclosure, so that it was like a little village, with floating islands around it with other buildings and inhabitants. This changed after we realized that the original scale of the space was too large and as a result, we needed to scale down the play area into one large room.

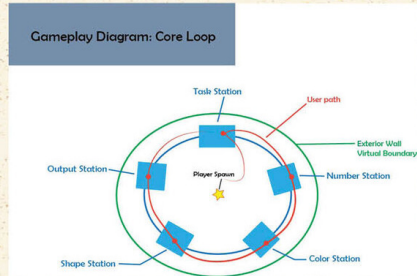


STATIONS 38

Gameplay & User Flow

We designed this play area to have all 5 stations within it and this room would be connected to another room where the user would be guided to after completing this binary math level. In the next level, the user goes to the next room, or the bubble sort level, where they can sort and arrange all of the shapes they made into animated configurations like candy trains, carts, or creatures.

Unfortunately, we only had time to complete the first binary math level, but we still drew out some of the visuals and prototype for the bubble sort level.



MACHINES AND ERGONOMICS

"In making the machines, I wanted to be sure each of them was unique and that the user could identify even from across the virtual space. The challenge was then making them function similarly to how they looked, without users having to spend a lot of time figuring out what does what on the kiosk. The pneumatic tube system had a lot of inspiration on our layout of the space, it served as the connection of all the machines showing the player their inputs and outputs were slowly bringing the space to life as conveyor belts and glass pipes whirled their task output about.

For each of the stations Jessica and I worked to make it seem like different stages in a coffee candy shop. The task station looks vaguely like a cash register, the output station the oven, and so on. Rivets and subtle widgets like dials or steam pipes flock over most of the many kiosks, while coffee beans litter some areas of the peppermint swirl flooring, sometimes even where the cream meets the conveyor belt stands. The world of CSpresso is alive and we wanted players

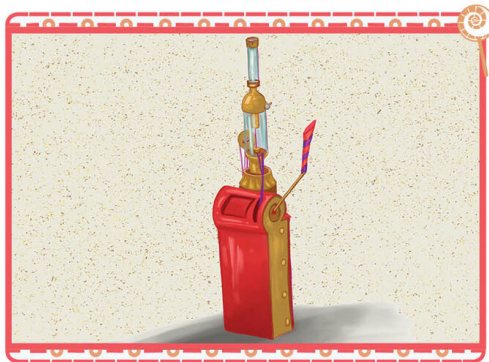
to feel that way as soon as they stepped in, rather than just a room with machines scattered within it and that was Jessica and I's greatest challenge.

Each machine has its own flair and attitude about it as some may be tall and have many levels while others may be short but span a large space, yet no two are the same. Every lever, machine, and gear I modeled had to have the end user in mind and Eric then tested to see what players thought could be improved. CSpresso's world is a fusion of mechanical caffeinated sugar infused learning and I had to make sure the machines embodied that. Many decisions were made about what Jessica and I wanted certain things to look like as concept designers and were always tested to make sure they worked for the user too as a UI/UX Industrial Designer too. CSpresso melds together the wonderful imagination of this world with ergonomic capabilities that help teach our user base in a fun and engaging way about computer science, that I hope will want them coming back for more.

- Brent Hartwell

Tutorial Station

This is the first station that the user interacts with. It is where the user is trained on how to use their hand controllers to make a fist and then pull backwards, which is the core interaction throughout the experience, for grabbing and pulling levers.



THE MAKING OF C-SPRESSO 41



STATIONS 42

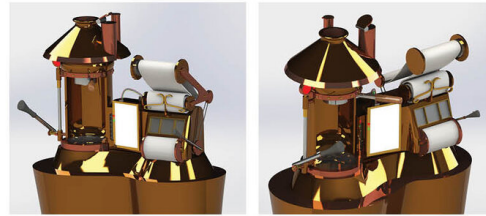
Figure H.8 Making of CSpresso pages 37-42.

Task Station

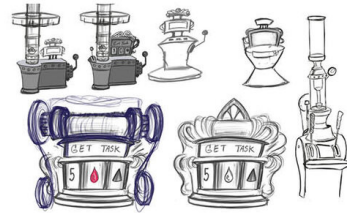
This is the first station in the main loop. It is where the user receives their task and where they complete their task. It will also alert the user if they did not complete the task correctly.



THE MAKING OF C-SPRESSO 43



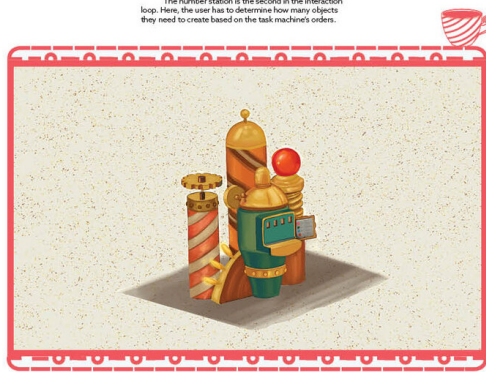
Task Station Concepts



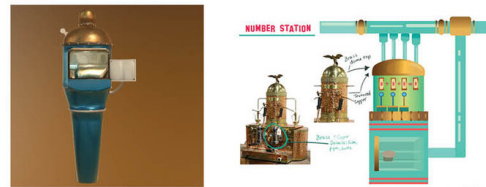
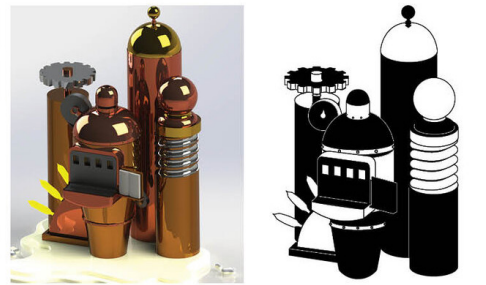
STATIONS 44

Number Station

The number station is the second in the interaction loop. Here, the user has to determine how many objects they need to create based on the task machine's orders.



THE MAKING OF C-SPRESSO 45



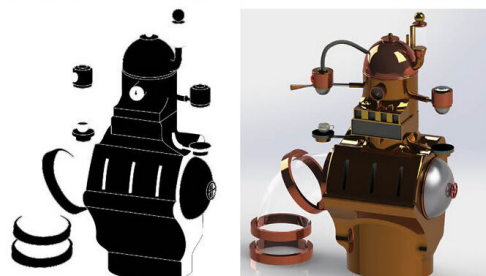
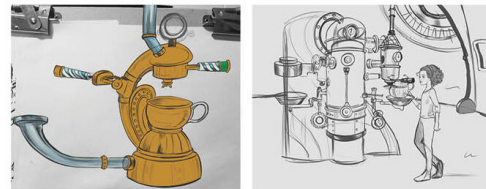
STATIONS 46

Color Station

Here is where the user gets to colorize their objects. They can even take a sip of coffee or tea from the two cups it holds.



THE MAKING OF C-SPRESSO 49



STATIONS 50

Figure H.9 Making of CSpresso pages 43-50.

Shape Station

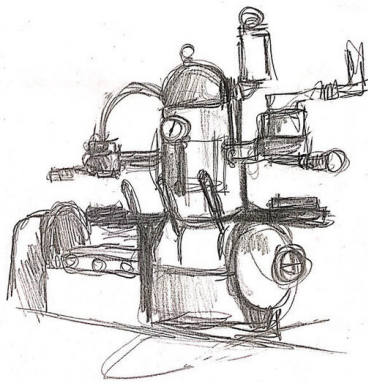


THE MAKING OF C-SPRESSO 51

This is where the user must set the exact shape determined by the task station. The most fun part is watching the objects roll out of the machine on the attached conveyer belt.



STATIONS 52



THE MAKING OF C-SPRESSO 53



BRENT HARTWELL

NOTE FROM THE INDUSTRIAL DESIGNER

This experience has been a wonderful example of reaching together both the technical workings of the real world and the fantastical ideas of Jessica's imagination. Jessica and I worked together to create the wonderful machines, gadgets, and setting of the world so that anyone delving in for the first time would be taken with the mechanical-crafted magic world myself. Eric, Jessica, along with our team had strived to build. As the Industrial Designer on the team I was in charge of the ergonomics, aesthetics/technical modeling, and any users would interact (UI/UX) within the world of C-Spresso.

We had to make sure users would understand and react to their surrounding assets in the world, so several stages of UI/UX testing were used to help us gauge what dimensions were desirable for all aspects of the machines and technical environments of the VR world. In testing my models and machines, I worked

hand in hand with Jessica, machines, kiosks, assets, and even Epic! would go through many iterations of drawing between us. We would see for example: "What lever worked better where, how could a certain pipe lead to something, would the user interact and react upon first sighting a certain asset?" All while maintaining the look and feel of the world we were building. We would work tirelessly on concept art to see the vision of the world through and I would then create then test the models with Eric in the VR world. As the Industrial Designer on the team I have a lot of fun while also finding the process very rewarding. I get to see a concept go through its entire lifecycle: starting with an idea, seeing what can change then test it, modeling again and again to go further with it, and then make it real. That's how I feel about C-Spresso, it's a testament to the team's intense work ethic and the promise of teaching Computer Science in a new, somewhat magical, and engaging way.

STATIONS 54

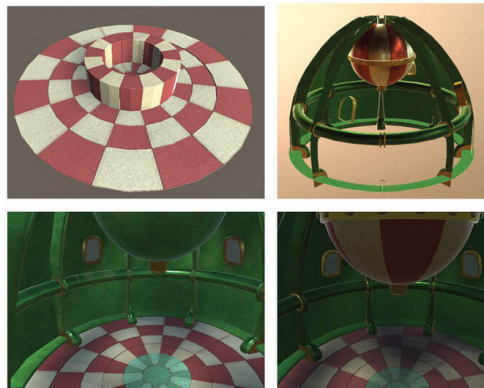
3D Textures

C-Spresso Station Room, Interior Environment



THE MAKING OF C-SPRESSO 55

3D Textures

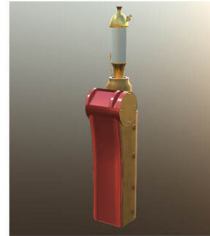
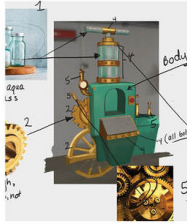


STATIONS 56

Figure H.10 Making of C-Spresso pages 51-56.

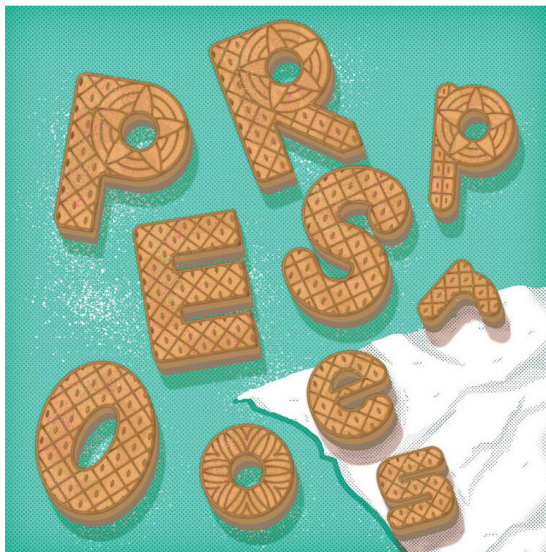
C-Spresso Station Room
SHANNON HARGRAVE

Left - OUTPUT STATION
Right - TASK STATION, TUTORIAL STATION



THE MAKING OF C-SPRESSO 57

STATIONS 58



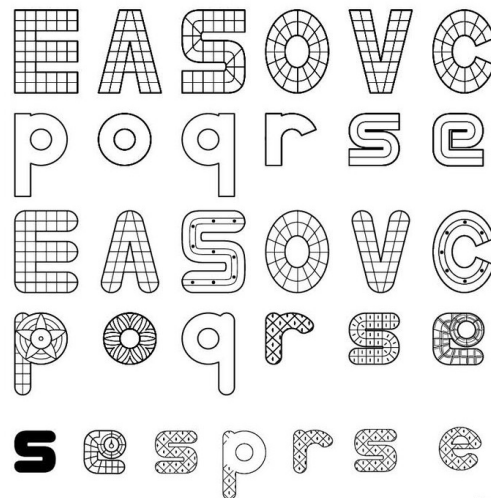
THE MAKING OF C-SPRESSO 60



THE C-SPRESSO LOGO - Designed by Jerry Bellone

When creating custom and stylized designs for branding and logos, often my goal is to take elements of a project, genre, or medium and implement it into the thematics and theme of the branding. In the case of C-Spresso, references provided to me were waffle cookies textures, brass, and candy flavored steampunk machinery. My initial focus in developing the letterforms was to focus on the cookie shapes, while also the structure, bolts, and plated feel of the machinery. After developing rough shapes for each letter (in hard corner and rounded corner forms) I started developing cookie and metal elements to apply to applicable letters and forms.

THE MAKING OF C-SPRESSO 61



BRANDING 62

Figure H.11 Making of CSpresso pages 57-62.



The first vectorized concept I created of the CSpresso logo involved different thicknesses for the letters to differentiate their importance to the structure of the word. Early on, alongside the cookie aesthetic, I experimented with a dripping-like feature, but this was scrapped come the second draft.

Starting with the second draft, I started to move to more thick and orderly, uniform aesthetics for the fonts. The biggest change between the second draft and third was making the whole "word" to be uppercase versus just the CS portion.

For additional elements to add to the letterforms, I adopted variants of levers, steam whistles, pressure gauges, and gears that are visibly apparent in the brass machinery in both concept art, and the models.

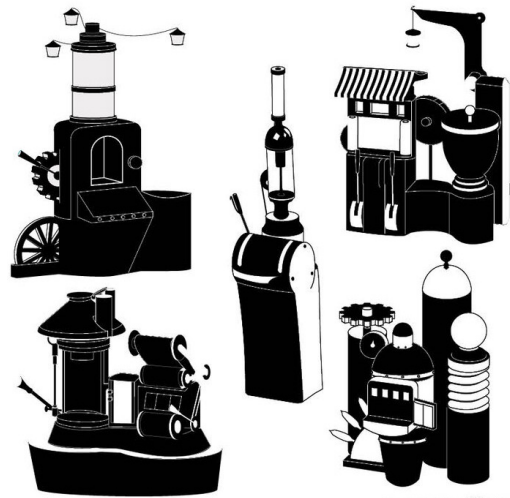
THE MAKING OF C-SPRESSO © 63



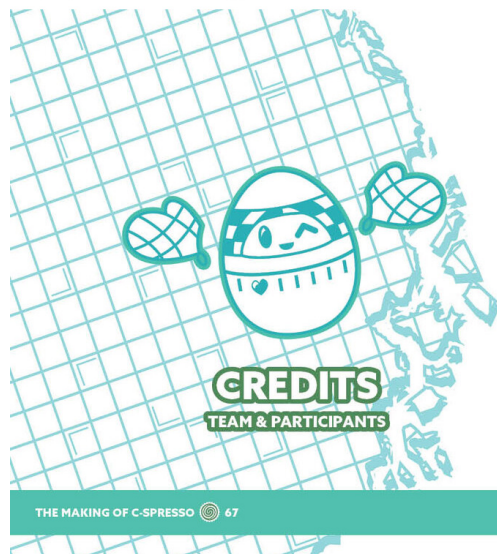
BRANDING © 64



THE MAKING OF C-SPRESSO © 65



BRANDING © 66



THE MAKING OF C-SPRESSO © 67

CREDITS

- | | |
|---|--|
|  Jessica Ross
Art Director |  Eric Nersesian
Technical Director |
|  Brent Hartwell
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UX/UI Designer, Researcher |
|  Jerry Ballone
Graphic Designer, 2D Artist |  Namita Mahindra
Research Assistant |
|  Shannon Hargrave
Textures, Data Analysts |  Cris Guzman
Modeler |
|  Todd Seelig
Modeler | |

CREDITS: Team & Participants © 68

Figure H.12 Making of CSpresso pages 63-68.



Figure H.13 Making of CSpresso back cover page.

APPENDIX I

SOFTWARE DESIGN - APP DESIGN BOOK OF CSPRESSO

In this appendix, you will the second of two books explaining the design of the software used in the binary counting study in chapter four. The basis of that software design was also used to build the software used in the bubble sort study in chapter five. The software design description excerpts are from “Making of” books that were presented at the Oculus Connect 6 Conference on September 25-26, 2019 at the San Jose McEnery Convention Center in San Jose, California USA.



Figure I.1 App design book of CSpesso cover page.

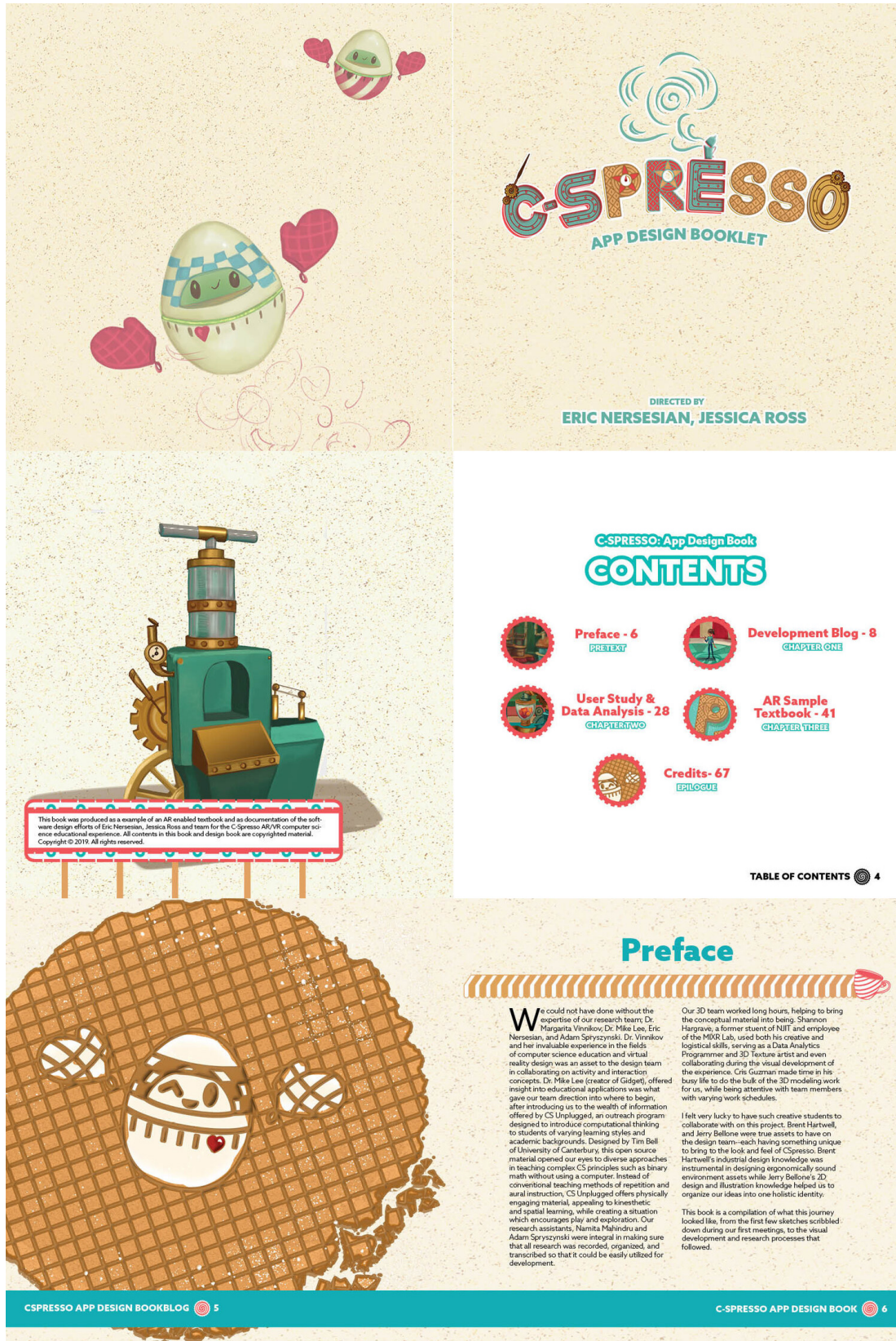


Figure I.2 App design book of CSpresso pages 1-6.



Overview

CSpresso is an educational application in virtual reality designed to teach basic computer science and binary math. The experience is designed around free moving abilities of the new Oculus Quest platform, which is completely untethered to any wires or computers, making it an excellent case study for learning environments involving physical activity within VR.

CSpresso is a name referencing the design of espresso and barista machines, which the quality designs of the kiosks and consoles resembled. Once this connection was made, the visual design began to take form, as designers researched various barista and confectionery machines such as grinders, cotton candy, and espresso machines. The creative direction for the experience is meant to maintain a light-hearted and fun mood, while users are learning complex and often intimidating math skills. The team hopes to immerse the users in a safe, engaging environment where he or she may explore, learn, and make mistakes, while having fun and playing.

The first goal of designing this application was to take full advantage of this new untethered feature, which would offer users another level of immersion as they physically move through virtual space. The virtual space is organized into a concentric circle, lined by consoles and kiosks, all chronologically placed into a clockwise direction. This design follows the order of interaction from start to finish, in one cohesive loop. The ability of the Quest allowed the team to incorporate spatial learning methods into the VR application, as the user walks from station to station, interacting, playing, and reaching for objects related to the lesson. Adding the element of spatial learning into the experience opened many exciting opportunities for the designers to explore while creating the environment, narrative and game mechanics.



Introduction

The world of CSpresso is one made up of 1's and 0's, candy, tea cups, coffee mugs, and space travel. It resides right in the center of the Milky Way, where inhabitants from all over the galaxy come together to share a pot of tea and enjoy sugary treats. It is also a vessel that is controlled by computer science and where you may learn binary math and coding.

In this immersive experience, you find yourself inside a spaceship that has been damaged during an intergalactic space storm. Here, you'll meet the ship's assistant,

Eggbert (but you may call him Eggy), a little egg timer creature greets you and grants you a quest to help repair the ship so it can get back home to the center of the Milky Way.



Adam Spryznski & Jessica Ross with early UX/UI diagramming on whiteboard.

Objective

Objective is to expose students to STEM and computer science in an engaging and immersive environment. Due to the Quest's untethered and free range of movement features, educators and researchers believe the CS application could benefit students who are visual and spatial learners. Spatial Learning refers to an individual's ability to perceive, analyze, and understand visual information in the world around them. As most US schools use a teaching method called Linear/Spatial Thinking, these students often struggle to learn the material or keep up with their classmates. In designing this educational experience, the team realized that auditory teaching methods (which include oral directions and sequential written directions), see the norm in public school systems and as a result, there are many students who fall short of benefiting from an education in computer science. Utilizing the immersive nature of VR and the ability to move within the space and interact with objects, this educational application in computer science may offer another avenue of learning to these other

learning styles.

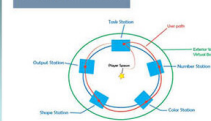
The experience must also be designed to be spaced through by experienced users, yet still be beneficial as refresher material to them.

At the end of the experience the user should understand how to solve binary math equations and possess a basic understanding of computational thinking.

This experience must be accessible, engaging, and have an adjustable pace to match individual learning pace; spatial learning aside from just aural learning, fun factor to attract a wider audience rather than those with an already present interest in computer science and STEM fields.



Gameplay Diagram: Core Loop



DEV BLOG 10

Dev Blog

4/3/19 - First Team Meeting

Today marked the first official day of development on the education app for Oculus Quest. The objective of this project is to develop an educational game application about Computer Science, using the new Quest from Oculus. This project will include a small group of UX/UI and visual designers, CS instructors, HCI researchers, and student volunteers.

Using this new hardware presents many exciting opportunities, due to the completely untethered nature. There are absolutely no wires or cables attached to the head set or controllers and there is even a camera placed within the headset, so there is no need to set up outside sensors. This offers the user the freedom to roam and move more freely around their physical and virtual spaces, lending yet another level of immersion for the user.

The timeline for this application is not entirely certain, aside from a potential user study on June 8th, with middle school children at a local STEM high school, here in Newark. The team has begun putting together basic parameters for what this application must include and how much of the overall experience should be completed by that time. Realistically, the end product for this deadline will be in a demo state, where the experience only includes the basic game mechanics and features. Setting these parameters of this expected level of completion makes the goal attainable and allows the

team to better prioritize this short time period. Some of these first priorities include what CS concept to teach, how to teach it spatially, how to make full use of the Quest's untethered functionality, and how to make the experience enjoyable, so that users are playing while learning.

The team began to kickoff the project with a brainstorming session, where members can begin exchanging their own ideas about possible genres, subjects, and interactions. Collaboration began to take shape once the researchers gave a few options of CS lessons to include in the experience. Some of the CS lessons included activities called, boolean algebra, building logic states, if statements, and logic puzzles.

The basic interactions and gameplay would need to be designed around these activities. One particular source of inspiration for CS activity lessons is an organization called CS Unplugged, a free collection of lessons and fun learning activities that teach both children and adults about CS. The materials are available from the website, which was put together by Computer Science Research Education Group, at the University of Canterbury in New Zealand. This source was an invaluable starting point for the team to begin building their experience, as the very nature of these activities is utilizing physical space and hands on learning without a computer.

DEV BLOG 12

Figure I.3 App design book of CSpresso pages 7-12.

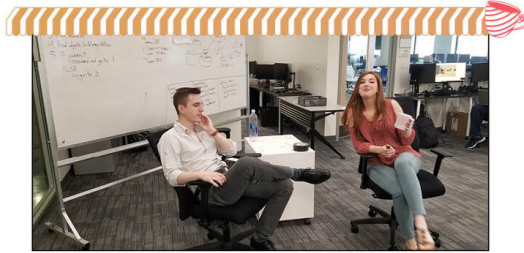
4/1/19 Opening Discussion

The team began the discussion of possible approaches for the coding experience in VR. Questions were explored such as, "What game would be used, what lessons in CS to teach and to what level of difficulty?"

Various CS learning activities and gaming applications were researched and discussed. This gave the team a starting point to begin brainstorming. Some of the gaming applications included in the brainstorming session were Tyrant, Alice, Scratch, and Kaio. Most of these digital CS applications used something referred to block code by CS educators, where the user would for one line of code by dragging and placing colored blocks into a sequence to produce the desired outcome. The Harry Potter application from Kano was a perfect example of how to gamify the subject of CS for younger audiences, which uses this block code method. Users have a hand held wand which they physically move in formulated

motion sequences, each with a different outcome.

The block code seemed to be the most focused and sensible method of CS learning to implement after trying out these other applications, but after more discussion the team realized that translating this technique into a virtual 3D space would not be effective. One of the main objectives for designing this application is to encourage the user to move freely and be active during the experience. More game mechanics and interactions would be drawn from this objective, so that the user could learn CS through spatial learning, within their immersive world.



C-SPRESSO APP DESIGN BOOK 13

4/23/19 Binary Math Lessons

After the team researchers decided to choose binary math for the learning objective, the designers began whiteboarding possible interactions. First, they would have to figure out how to represent binary numbers in a 3D space. This concept would be represented in the experience as levers the user would pull up or down, to change a number from 1 to a 0 or vice versa.

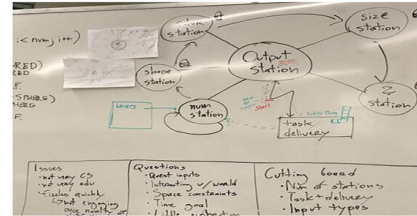
The levers would have 2 positions so as to not distract the user from the 0 or 1 action. There would also need

to be a display at this station which directly reflects the actions of the user.

The experience was wireframed in a concentric circle pattern, where the user would start and finish at the same location. They would need to be an introduction to acclimate the user to their virtual environment and teach them what to do. The designers wireframed a user flow similar to an assembly line, where the user would move from one station to another station, to complete a task.

These stations became central to the interaction design of the experience:

- Output Station (OPS)- User would need to train for the OPS first
- Color Station (RGB) the user would be given a color to match with 3 dials. For example the color, aquamarine's binary representation is RGB value 66,244,238
- Task station- Where user goes to get a task.



DEV BLOG 14

Differing Levels of Knowledge & Experience

The development team realizes that there is no way to know what level of computer science and binary math of each user. Due to this reality, there must be multiple levels of the experience, starting with an introductory level and gradually getting more complicated as the user excels through each level.

To avoid frustrating users who are already experienced in computer science and binary math, there will have

to be a feature that allows the user to skip levels that seem too easy and jump ahead to more challenging levels.

There may also need to be a feature which allows the user to select their level of skill; beginner, intermediate, advanced. Having this ability in the experience would offer the user to tailor the lessons to fit their comfort level.

Space & Ergonomics

In the first prototype, the stations are built like small kiosks and they were placed very close together. After going through a rough floor plan of the experience, the layout of the kiosks was modified. The space seemed really large, so it was concluded that this would change as a result of adding more assets which would populate the scene, such as the dome enclosures that would be around each kiosk. A cylindrical wall has been added around the entire floor space and this drastically made the space feel less spread out and empty.

Considering the ergonomics of these kiosks is another

challenge because this experience will be tested with middle schoolers and adults, so the height to build these kiosks is currently unknown.

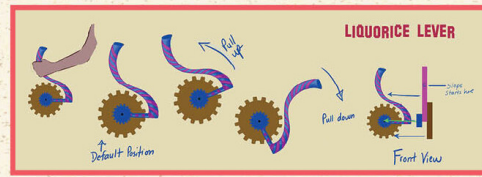
The kiosks will be designed to be ergonomically sound. This means that the dashboard with the controls need to be placed at a level where the user does not need to bend down or tilt their head up. The width of the dashboard, ui, and display also needs to be designed so that it is within the scope of the user's vision. If the kiosk is too small or too large, it will not be comfortable for the user to interact with.

User Personas

Before moving forward with the visual design, storyline, and theme of the experience, the team will be evaluating who the target audience is and how to collect information on what they are drawn to, visually. The users previously tested, were ages 10-12 and were varied in gender and ethnicity. In the US, it is widely believed that the appropriate age to introduce users to VR is 12. Due to this age minimum, it is most beneficial to focus on ages 13-16, when most students are typically introduced to computer science. Moving forward with future testing and for the continuation of development, the team will be focusing on middle to high school students, making the ages 13-16 (7th to 10th grade).

This is not to say that designing and testing other VR experiences will be exclusively on these age groups, as the team believes it will be highly beneficial for younger students (ages 11-14), to be exposed to VR and have a helpful outlet to learn computer science.

Another key focus for the users in which the team is designing is in underrepresented minorities in STEM, such as females, handicap, and ethnic students. These groups of children are in need of better access to education within the STEM field and so this is the core intent at the heart of developing this experience.



C-SPRESSO APP DESIGN BOOK 15

DEV BLOG 16

5/7/19 - Space and Ergonomics

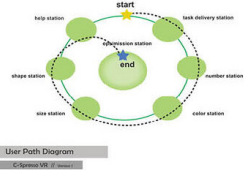
The next topic focused on was the matter of space and ergonomics. In the prototype, the stations are built like small kiosks or game consoles, about 6 ft tall. There are currently 4 stations all together and are arranged within a circle, to indicate the flow of interaction for the user.

After seeing the interior design of the station in 3D space, the design team felt that the space was too small and cluttered. To solve this issue, the design team altered the original floor plan of this space so that there was more room between stations for the user to walk through. The 3D model was updated to fit the new design, being careful to leave enough room for the transparent domes which are meant to be over each kiosk, making 5 independent small stations placed around the one main Mission Station (as seen here in this illustration).

Unfortunately, due to the time constraints, this idea was cut so that all 4 stations are within one dome, making it one whole station. The original layout design for this environment is being archived for the next phase of development.

The next challenge would be to design the interior environment to accommodate our target audience. The issue with this target audience is the wide array of heights to consider, due to the varying growth spurts of puberty. Focusing on middle school children is a challenge for this reason, as it encapsulates the beginning of those pubescent years, which are typically 10-13 years old in boys and even earlier in girls, from 8-13 years old. This made the concept of predicting a common height to build around, very daunting because height is particularly hard to predict depending on when the individual's growth spurt begins.

Currently, the team is spending time on some light research into what average height to build around, depending on all of these factors. The objective is to build a space that is "ergonomically sound" for as many users as possible. This means that the dashboard with the controls need to be placed at a level where the user does not need to bend down or tilt their head up. The width of the dashboard, UI, and display all need to be designed within the scope of the user's vision and height. For example, if the kiosk is too small or too large it will not be comfortable for the user to interact with.



C-SPRESSO APP DESIGN BOOK 17

5/8/19 - Prototyping and First Round of Alterations

Changes were made to the initial 3D prototype of the stations after the team evaluated current progress on these designs. One of these alterations was the name plate, positioned on top of the station. This nameplate added extra clutter to the kiosk's surface and if the station is designed well, there would not be a need for a label of what that station is. If after the station is designed and the team feels that reinforcement information is needed for the user, then the written name plate could be supplemented with icons, which offer a quicker way to deliver information and don't add much clutter.

Each station's UI was carefully observed in 3D space, then altered accordingly. The number station proved to be the most time consuming, as there are multiple functions and interactivities needed to complete the task.

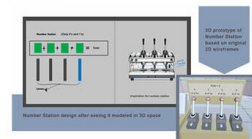
The design team went back to wireframing to brainstorm the best way to organize this information. This was a long, yet rewarding process, resulting in a much improved wireframe of the number station. The design team first drew out the UI of the number station and realized the display screen may be too confusing for the user to read because it contains both the total and the equation.

In the diagram below, the levers are directly placed underneath the corresponding numbers and the total is at the end of the equation, as it would appear in any mathematical equation. With these changes added to the UI of the number station, the team is more confident of the user's understanding of the station.

The team is currently discussing the options for navigation within the experience. Due to time constraints, the option of having a character guide to bring the user from station to station, is not feasible. This leaves only a few other options which include voice over prompts, text panels or signs, and adding constraints to what the user may or may not be able to do, to prevent them or help from getting distracted and swerving off course. Other possibilities included visual cues such as blinking lights, which may appear at the feet of the user when the experience begins and then projects outward in a dotted path to direct the user where to walk.

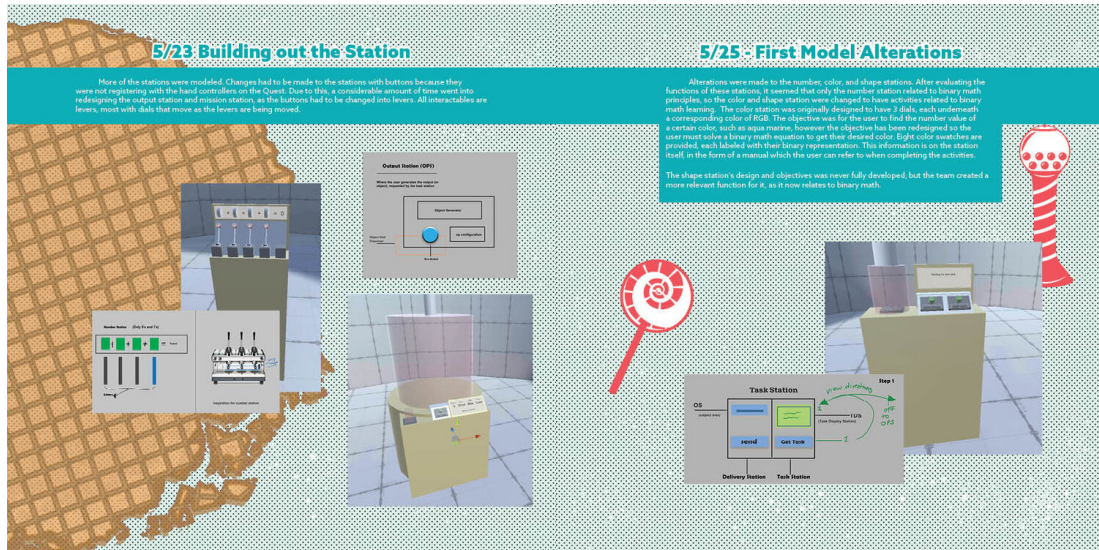
Another possibility is to include a station dedicated to help and guidance. This station, the Help Station, will have elevation controls (up or down), to take the user from one level of the station to another. These features would include an interactive map of the entire play area and other information to help guide the user through the experience such as clues, guides on how to use the different stations, and a guide to binary numbers just in case the user does not understand the number station activity. After working out the current timeline until the June 8th deadline, this idea was archived along with the character guide.

For the time being, the team has decided to stick to either voice overs or text boxes, which are much quicker to implement. These more elaborate options will be revisited after the June 8th deadline.



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Figure I.4 App design book of CSpresso pages 13-18.



Model Designs

BRENT HARTWELL

Final Models

SHANNON HARGRAVE



Brent's technical models were the starting point for us to see our concepts in 3D. The number station was challenging due to the amount of information that had to be provided. This color station design was based on a few vintage espresso machines. Brent had fun building out the wonky shapes and adding fun elements like the cup holders on either side.

Shannon's texturing was the final step in bringing these stations to life. The texture and number stations were particularly challenging due to the varying patterns and textures used all over the stations. Despite this, we were always impressed with his final renders.



C-SPRESSO APP DESIGN BOOK © 23

Future Level: Bubble Sort

During today's meeting, team members discussed upcoming deadlines, goals, and how to continue designing the experience. All team members agreed that another activity would have to be brought into the gameplay to break up the stations activity. One way to do this is to introduce Bubble Sorting, which is a CS term referring to a sorting algorithm that works by swapping adjacent elements if they are not in the correct order. This process is repeated through a list of different values until the entire list is sorted.

First, the team set up a paper prototype of how a Bubble Sort activity would work. This was simply done by writing 7 different numbers, each on its own post-it. Team members who were not already familiar with this concept practiced swapping the adjacent post-its down the list, keeping the larger number always to the right of the lower number. This process was then followed by taking physical objects and sorting those within the space that users would be playing in, during this activity. Boxes with different numbered post-its were placed in a half circle arrangement and team members collaborated on different fun ways to incorporate

this concept into the gameplay of the current prototype.

After these paper prototype exercises, the designer collected all necessary information on what was observed during the prototyping and began to draft concept sketches of how this Bubble Sorting activity could integrate into the game. One team member wanted the user to sort containers of objects, created during the stations portion of the game and another team member preferred that the user sorted pegs with different number or size values assigned to each one.

Regardless of what was going to be sorted, it was understood that a reward at the end of the activity was crucial, to give the user a sense of validation after successfully completing the exercise. This is how the assembly portion of the experience was formed. Once the user completed the bubble sorting activity, he/she will be able to assemble something from the objects created in the stations area. More thought is being given to how to bridge these concepts together, but currently the team has these concept sketches to pull ideas from.



DEV BLOG © 24

Figure I.5 App design book of CSpresso pages 19-24.

6/8/19 - User Testing

Today, at Science Park High School in Newark, the team was able to watch several groups of middle schoolers play in the Oculus Quest app. The team who attended this user study consisted of two researchers, a developer, and a designer. Middle school teachers also came to watch the study as their students walked around the gymnasium in the new Oculus Quest headset. Students were first interviewed after participation in the experience. Each group consisted of 5 students who were placed within a 20' x 20' ft confined boundary space marked with blue masking tape. Students were then instructed to begin the experience, which would be timed for approximately 15 minutes.

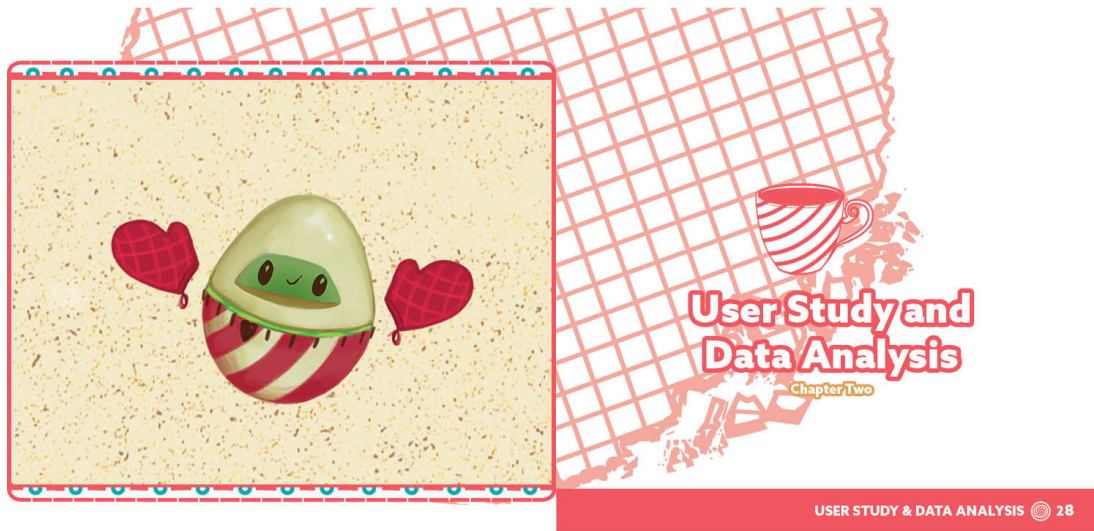
The outcome of this user study was positively rewarding with a few students opting to play a second time. The overall impression received from observing the students

was that the experience, even in its rough state, was engaging and fun. Students made full use of the Quest's untethered feature, breaking out into victory dances and freely moving about in their 20 by 20 foot space. A very small number of students did not seem to enjoy the experience, but after talking to them, it was unclear if the negative feedback was due to the platform of VR, or the design of the experience, after the students described motion sickness and eye strain.

Other than observations and brief verbal feedback between the supervising designers, students took a post test and were interviewed about the experience. The team hopes to learn much more about the feedback from these interviews and plans on moving forward with development based on this feedback.



By using the gymnasium at Science Park High School as a navigable space, Eric, Jessica, and Rita help prepare and guide students through the lesson prepared for User Testing of the Oculus Quest.



User Study

RIITA VIMNIKOV

We conducted a user study with a group of middle school students attending a summer programming camp called "Newark Kids Code." The camp was hosted by the Science Park High School in Newark, a magnet public school of Newark, NJ. The school teaches ninth through twelfth grade with a focus in science, technology, engineering, and mathematics. The mission of this school is to prepare students for potential careers and study in these rapidly evolving and growing fields.

We used this setting as a pilot study to test the feasibility and applicability of using Oculus Quest standalone VR technology in school settings. We chose a binary math lesson to compare the effectiveness of learning with VR technology as opposed to the traditional approach - teaching standing in front

of a class. Specifically, we compared a controlled group that got a traditional lesson on binary math conducted by Dr. Lee versus an experimental group that got to learn about binary math from trying our application in Oculus Quest.

Before starting the experiment, we looked at students' prior knowledge through a pretest and compared the results of how well students learned from both the traditional and VR techniques.

Formal results are yet to be released but below are some of our lessons learned from this experiment.



Results

The outcome of this user study was highly rewarding with a majority of subjects going past the recommended playtime and a few students opting to play a second time. The overall impression received from observing the students was that the experience,

PRE AND POST ASSESSMENTS

is where we will see a significant difference between a standard lesson and hands-on VR technology.

The analysis of the learning assessments indicating the VR users learned binary math just as well as the group taught by Dr. Lee. Meaning that the VR experience is just as educational as an instructor-led lecture without the variability of instructor quality and restrictions on instructor availability and locality. These results revealed that the Oculus Quest experience is, in fact, educational, and suggests that it may have some benefits over traditional teaching methods. In future studies, we would like to look at the student's recall of the lesson learned over a period of time. We believe this

Below is Dr. Lee's analysis of the learning assessments indicating the users in VR learned binary math just as well as the group who Dr. Lee taught using CS Unplugged.org methods. The classroom exercise consisted of cards with different binary numbers on the front and back, which the users had to flip up or down, to represent the desired number in binary.

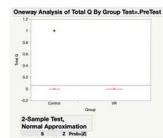


FIGURE 3

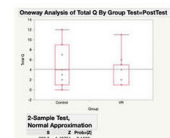


FIGURE 4

Figure 3 shows that the control condition and the experimental condition participants both started off the same score that is close to zero. In other words, they did not know how to count in binary. Next, Figure 4 shows that after either a lecture or VR experience students' scores got significantly higher. However, there is no statistically significant difference in their

post-test scores. This means that both the lecture and the VR activity were statistically equivalent in their effectiveness teaching the students how to count in binary.

Figure I.6 App design book of CSpresso pages 25-30.

Interviews

We have conducted group interviews with all students who participated in the study. We decided to interview students in groups of 5 people per group. Dr. Vesilov who has more than 10 years of experience in HCI research and a certified teacher conducted the interviews, while the students were accompanied by another teacher who they have known from the program. Although the literature suggests hosting

individual interviews or with 2 students at a time, we opted for a larger group for two reasons. First, we wanted the students to feel more comfortable with their peers and also we did not have time and resources to interview 2 students at a time. Each group that we interviewed took 10 to 15 minutes to discuss the key questions outlined in Dr. Vesilov's script. All interviews were recorded and transcribed for further analysis.



KEY FINDINGS

Effortless and intuitive interaction: Students felt that learning was natural and easy. They also liked to see their hand motions and the natural interaction through hand gestures. Most of all, students liked the ability physically walking in VR.

Request for more content: Students really like the provided activities and wanted to participate in more similar activities as they felt the task got redundant toward the end when they grasped the main concept taught by the activity.

Gender-specific feedback: Requests for action and exciting events such as explosions from the male students while the female students were happy with the ability to take their time and solve puzzles and have the virtual environment calm and quiet.

Other Requests: Students wished to have a guide or a friendly helper during an experience and also to see other body parts besides their hands.

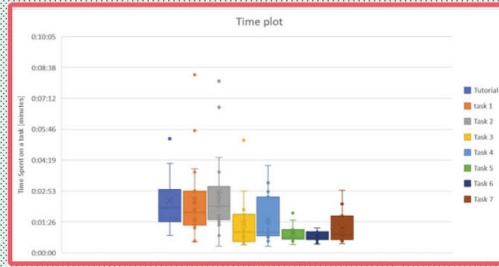
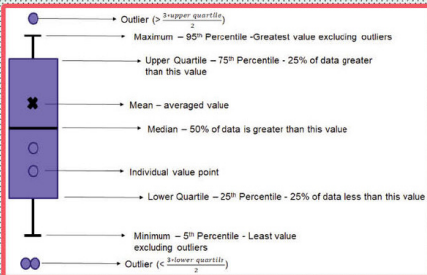
Other Issues: One student found the headset to be heavy.

- What did you like the most? What was fun? Did you feel engaged?
- What did you dislike the most? What was the most challenging aspect of using the Oculus Quest?
- Did you learn anything while playing Oculus Quest?
- Did this exceed your expectations? Would you hope to see/do something different?
- How hard/easy it was to use the controller? Was it easy/hard to select/manipulate objects?
- Were you dizzy? Did you feel uncomfortable? Sick?
- Did you find the tutorials helpful? Why? Or why not? Could you figure things out without a tutorial?
- Did you like physical movements? Did you like walking while learning/playing?
- Did you need to stop early?
- Where you comfortable for a whole time? Did you want to stay longer or less?
- Did you experience any blurriness?
- Would you like to play on a computer or a headset?

Positional Data

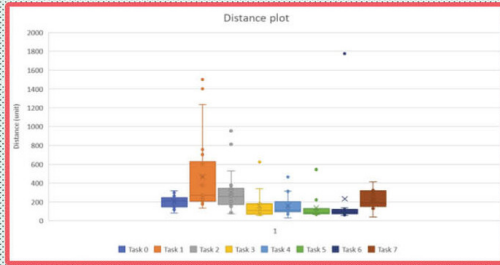
The current technology does a great job of providing a very rich user output and to minimize the hardware related constraints. For example, Oculus Quest offers a very extensive range of free movements and mobility to the users. Our user interviews have shown users really enjoyed their experience overall and our post-test scores showed that users learned as much as during a regular class. However, our personal observations, some interview notes, and notes recorded

during the indicated that not all the participants had similar experiences: some struggled at the beginning, some got bored at the end, some had technical issues during the VR experience. These instances can be identified on individual bases, but as researchers, we are interested in quantifying the data that can be collected from the head-mounted device and on the methods on how we can analyze and offer important information from positional data.



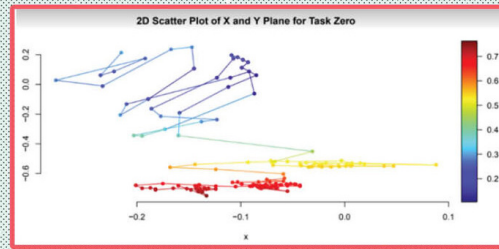
Time Plot

The time plot shows the time distribution across participants for each trial that the students participated. From the plot one can see that it took the longest to go through trials 1 to 3, where after that the time for tasks execution got shorter. This can be explained that the learning process took place across the first 3 trials and then as students learned the task they got more effective at completing similar tasks in less time.



Distance Plot

After looking at the time spent on each task distribution, some may ask what were students doing during the task. Without looking through each recorded session, we can offer the positional data to get more information from looking at the virtual distance walked during each task. When looking at the data one can see that during the first trial students did not walk much, but on the other hand they did walk a significant amount of distance in doing their second trial, and only then the distance walked was significantly reduced, except for the last task, in order to explain what exactly happened we looked at the positional plots.



Scatter Plot

TUTORIAL TASK
This is an example of a student going through a first trial, that was a tutorial trial. One can see that although a person was moving, they stayed close to each station. This can explain the fact that it took students quite some time to go through tutorials and explore each station but they did not move far away from the stations.

Figure I.7 App design book of CSpresso pages 31-36.



Figure I.8 App design book of CSpresso pages 37-42.



C-Spresso

All sweetness in the galaxy comes from one secret location, smack dab in the center of our Milky Way. If you are ever lucky enough to make it there, you will realize that the very air you breathe tastes like the inside of a bakery or maybe a candy store. At that point in your journey, you will know that you are approaching the hidden city of Dessert Star. If you've ever wondered where the very concept of sweets and treats originated, it is here. The atmosphere of Dessert Star is completely made up of a chemical compound called ethyl formate, which gives earth the scents and tastes of everything sweet, from fruits to candy, and even flowers.

The C-Spresso is Dessert Star's most iconic and significant space station. Here, all of the galaxy's sweet treats and confectionary delights are manufactured and distributed to all inhabitants within the Milky Way. This helps keep the peace within the galaxy, keeping everyone happy and peaceful, with sugary treats, nice hot coffees, and even tea time... especially tea time. All within the galaxy love coming to the city of Dessert Star, to unwind from a hectic work day, or to share a pot of tea with other nearby, intergalactic friends. While Earth is within the Milky Way, it is just too far away to visit in time for brunch or tea time, so

the C-Spresso makes its rounds along the Milky Way, doing air drops of coffee beans, sugar cane seeds, and tea leaf plants for the little Earthlings to harvest and distribute among themselves. The next time you find yourself enjoying a candy cane, liqueur, or hot cocoa, you could appreciate this magical place far away in the center of the Milky Way, that is rumored to taste like raspberries...and you will know why!

It has been this way for centuries, and has kept all within the galaxy happy and full of cheery energy. Unfortunately for them, an asteroid has just torn right through the center of the Milky Way, splitting the docking station where the C-Spresso recharges between rounds and hurling it far off into space. The inhabitants of the galaxy have since been in a frenzy, trying to locate the ship and bring it back to Dessert Star.

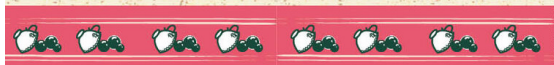
Someone brave will have to go out into the inky blackness outside the Milkyway, find the C-Spresso, and bring her back to Dessert Star, so that everyone's lives can go back to normal. Until then, the inhabitants of the Milky Way will be dreaming about when their ship will be back so they can warm up, after a much too long period without delightful hot beverages or



Eggy

Eggy's going to want you to start the phone app and you will be guided through the experience. Center the phone on the right page because there will be UI on the sides and the app will guide you through the rest of the experience and get ready to learn about bits and how computers count numbers with C-Spresso's binary math lesson. Remember, Eggy will show you how to use those trackers on the right page, always look on the left page to read the directions and your phone on the right page.

"The asteroid really knocked everything out of order! I'm running out of power after trying to clean everything up by myself and trying to stop all the sugar goblins from eating all of our remaining fuel. The C-Spresso's computer system is down and the ship won't move until it is fixed. None of our fuel can be processed throughout the whole ship if we can't fix this system and I'm starting to really lose it with the Teacup Monsters and Sugar Goblins who are wreaking havoc on all of the spilled sugar and candies! Could you help me repower the station? If you do, you'll get some of the best treats made here on the C-Spresso for life!"



Tutorial Station

"Welcome to the tutorial station! Here, I'm going to train you on fixing the system. I'll be guiding you through the rest of the level, one station at a time. First, we need to understand how to use a bit. A bit is a way that computers keep track of information and count numbers. Just like humans use their fingers to count from 1-10, computers only use 1 bit which is 0 or 1 to count. Computers can use a series of bits to keep track of long numbers or they can use them to keep track of a list of objects. Here we're only looking at one bit. I'm going to show you how to track that candy dish and when you do it's going to turn into a bit and make that bit into a 1. Follow me and learn how to turn a bit into its two states, either a 1 or a 0."

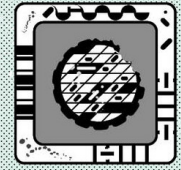
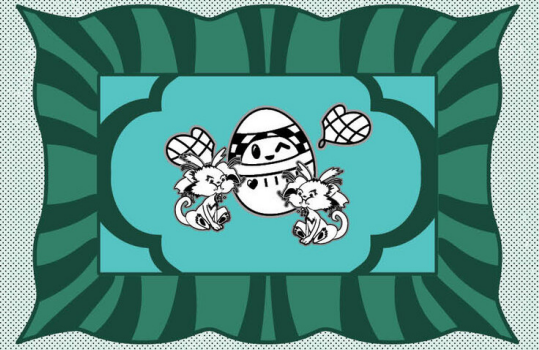


Figure I.9 App design book of CSpresso pages 43-48.

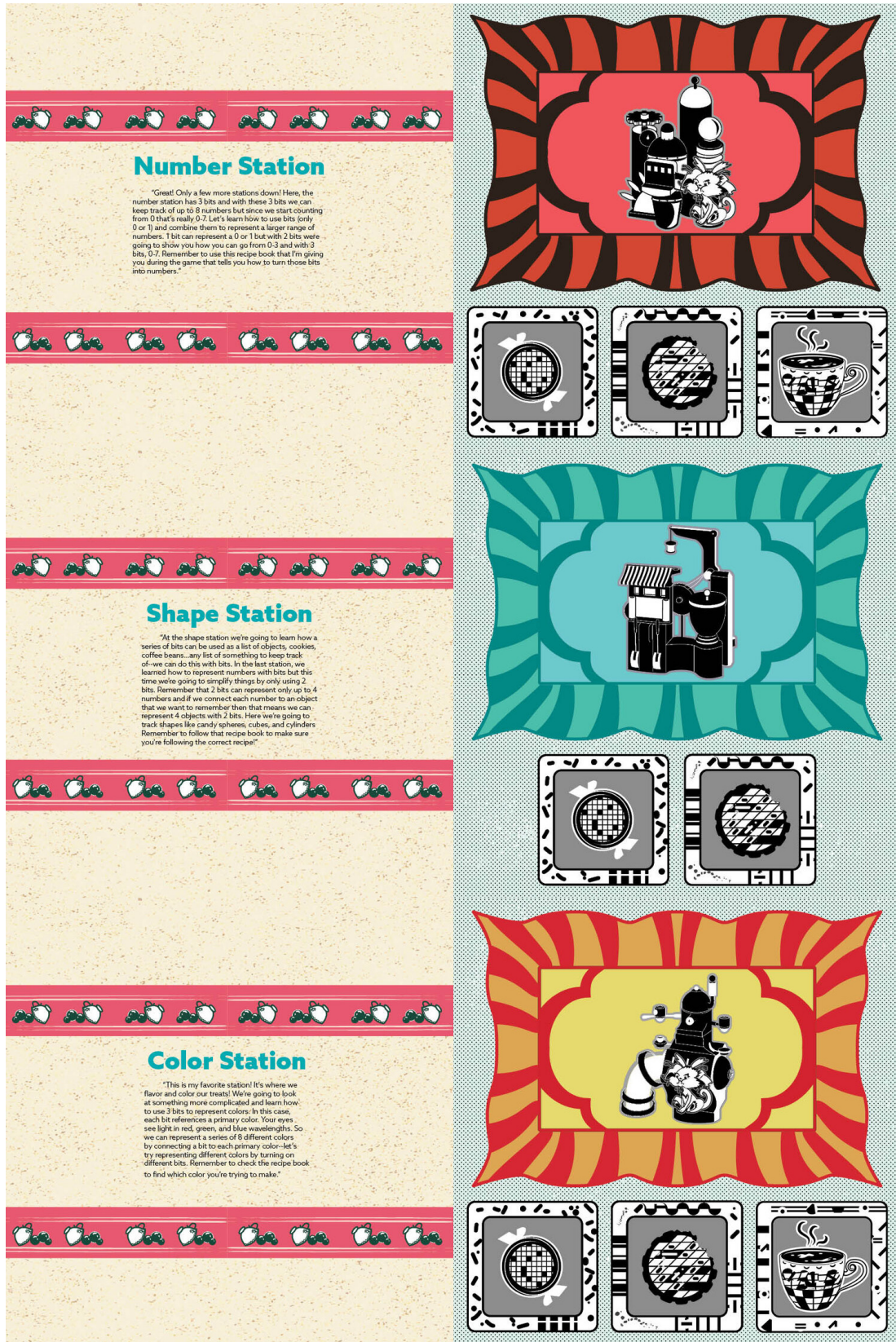


Figure I.10 App design book of CSpresso pages 49-54.



Figure I.11 App design book of CSpresso pages 55-59.

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