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Effective Immersive Analytics for Everyday Use

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EFFECTIVE IMMERSIVE ANALYTICS FOR EVERYDAY USE

by

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A Thesis

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Dedications

I would like to dedicate this manuscript to my friends, family, and to those who were unjustly affected by the devastating response and results of the ongoing pandemic within the United States. Hopefully, with the assistance of visual analytics techniques and development of the emerging field of immersive analytics, we can learn how to tame such crises without sacrificing the most vulnerable individuals within our society.

Acknowledgments

I would like to thank the Rowan University Computer Science Department for

all the support amidst a global pandemic during this research endeavor.

Abstract

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EFFECTIVE IMMERSIVE ANALYTICS FOR EVERYDAY USE
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Data visualization is an important field of work that takes in uncountable amounts of indexes to create an easy-to-read interpretation of what was previously unreadable. Immersive analytics is the new field that brings 3D data visualization to virtual reality, immersing users directly into the data. Focusing on bringing humans and computers closer together through natural function can benefit the world of data science. In order to accurately utilize this field to benefit this world, principles must be laid out and observed to see which techniques and methods are best fit for an everyday immersive analytics platform. Our findings show that, within an immersive 3D environment, users that perform in a static state where no physical or virtual navigation of the environment is present is more beneficial to the interpretation of the data. While reported gender identity does not seem to affect the time to complete the given task, it seems the age of a given participant is one factor which affects the task time.

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Chapter 1

Introduction

1.1 Introduction

Immersive Analytics is a new and emerging field in data analytics. Utilizing Virtual Reality Head-Mounted Displays in collaboration with hand-tracking technology provides immersion and natural experiences to the user. Integrating natural intuitive motion to data analysis can help analysts achieve a deeper understanding of visual analytics when exploring a virtual space. Our study aims to test the effectiveness of immersive analytics techniques with the relationship between interaction and locomotion within a 3DUI (Three-Dimensional User Interface) virtual environment. Conducting visual analytics using 2D spaces can be limited in what can be viewed in the data compared to 3D spaces. With a 3D virtual space users can take advantage of another dimension to visualize the data they wish to represent. Immersive analytics aims to bring 3D data visualization into virtual reality. With the rise of big data in the field of computer science, data analytics is necessary to process the information collected. When we are faced with the large volumes of data that come with this outcome, efficient and effective data visualization is important to accurately interpret what the data holds [50].

1.2 Motivation

1.2.1 Visual Analytics

Visual Analytics technology is built on the science of analytical reasoning. This process involves understanding historical situations, identifying current scenarios or future events, and other supporting decision-making actions in a time of crisis. Visual representations and human interactions, combined with data representation and the analytical process, visual analytics can be used to view data in different perspectives to see if the data can give insight from real world scenarios [47].

1.2.2 Immersive Analytics

Immersive Analytics (IA) is an emerging new field in the research of data science. IA refers to technologies utilizing 3D data visualization within an immersive environment. A good example of an immersive environment would be one inside of an HMD (Head Mounted Display) whether it be in VR (Virtual Reality) like the Oculus Rift, or AR (Augmented Reality) like the Google Glass. These technologies support data analytics within a 3D space for immersion with the environment around the user. Other technologies such as CAVE (Cave Automatic Virtual Environment) which is another form of immersion that consists of high-resolution screens around the user, however these can tend to be much more expensive compared to their head-mounted counterparts [38][4]. CAVE environments, whether it be the original CAVE from 1991 or the 2012 version titled CAVE2, can only support a limited number of people at a time. Utilizing

HMD for IA can be a pathway to support multiple users in each environment at a cheaper cost than the CAVE environments [16].

This new field of study can bring innovation and opportunity to data analytics. Creating immersive environments for people to interact with is the first step to creating natural interactions between the user and the data [6]. Not only that but bringing data into 3D virtual spaces can allow for more varied design, bringing flexibility to design choices. Giving both users and designers more freedom in exploring and creating data visualizations is important for a natural immersive experience [33]. Along with this, the qualitative experience of users has seen to improve when using IA platforms. Higher usability, user preferences, low simulation sickness, detection of clustered data, and lower measured mental workload can be achieved through this technology [19][26]. IA can be engaging, interactive, and collaborative between users. Connecting virtual reality with immersive integrated worlds can bring new perspectives and opportunities to data analytics technology [36].

The challenges that come with using IA come in plenty. The ability of users being able to see clearly through high-resolution screens is important, if users are unable to see the data clearly on an even level it could prove troublesome. Supporting interactions between the data and users by allowing them to add, remove, and save data accordingly, as well as user tracking, and a quiet room with enough comfort to work multiple hours at a time [14]. Natural light may also interfere with some HMD and other immersive technologies. The information being displayed to the user is important. IA can be used to decrease the mental workload of working with data analytics but overloading the user can

have the opposite effect [30]. All these factors are to be considered when designing an immersive environment for use.

1.2.3 Stage of Immersive Analytics (IA)

These techniques have a positive impact on data analysis as a whole. Giving a visual representation and meaningful ways to interact and transform that data is important for researchers and analysts to be able to observe and tell the story the data holds. Improving the field of visual analytics is essentially improving our understanding to prepare for specific events [47]. If we can analyze the data that is taken from real-world situations and apply it to visual analytics, we could better understand how to prepare for those real-world situations accordingly. Since IA is an emerging field of visual analytics, many guidelines are needed to establish its fundamental principles, particularly on 3DUI.

1.3 Research Goal

The goal of this research is to provide comparative analysis on 3DUI designs of IA operated on typical information datasets, abstract datasets that do not consist of 3D data attributes. The goal of performing this research task is to narrow down the ways in which data can be visualized in an immersive environment effectively. This is done by comparing two different views; a bird's eye view and a grounded view, with three different modes of locomotion; sitting/stillness, walking, and teleporting. An effective conclusion can be approached by comparing these scenarios to see which methods work

well together and which methods that do not work well. The ultimate goal of this research is to provide effective everyday use of data analysis in a 3D immersive space.

The main question of this thesis is to ask, "If utilizing immersive analytics can provide more insight to a dataset, how can the data be displayed most effectively in an immersive space?". To help answer this, the following questions will be addressed in this thesis:

1. In what ways can a user navigate through an immersive space, and which is most effective?
2. In what ways can a user interact with 3D data visualizations in an immersive space, and which is most effective?
3. Which combination of locomotion and interactivity appears to be the most effective?
4. Does the utilization of hand gestures via hand-tracking to manipulate data increase effectiveness?
5. Does the spatial ability of a user affect the outcome of using immersive analytics?
6. Do human factors, such as age, gender, and the VR Game Experience of a user affect the outcome of using immersive analytics?

Chapter 2

Background and Related Work

2.1 Immersion

Immersion refers to the state of surrounding the user with a given environment. Not only could immersion assist data analytics with the field of IA, but immersive technologies can also assist the training of real-world situations. From manufacturing and assembly to surgical training, everyday researchers can be assisted through the lens of immersive innovation [5][11].

Deciding which technology to use can also affect the level of immersion a user experiences. Utilizing HMD or a CAVE environment is important to distinguish, however there have been findings to show that with no significant differences in accuracy or communication, the cost effectiveness of HMD is proving its worth in the exploding field of immersion research [13][24]. The use of hardware is not the only factor to consider when designing an immersive environment. For example, personalizing virtual body parts can seemingly add to the immersive experience of the user by adding to their feeling of presence [40]. Design choice of the aspects of immersive environments, especially in IA, is important to consider. According to [8] visualizations that are created feely suspended rather than stuck to a given location like a virtual table or wall can provide this immersion to users. Even aspects like crafting a clear background, or Skybox in immersive environments, are important to establish so users do not become disoriented in the environment. Using data with conflicting color schemes or other visually impairing methods could render data exploration useless [31]. Users are interested and excited to

utilize this technology as it can help them gain new meaningful insights to the viewed data. Immersion can provide these new insights into data visualization as the field of IA and other 3D data visualization fields evolve [20].

2.2 Natural User Experience

Alongside immersion, the natural user experience is important to establish within IA and other immersive technologies. A natural user experience is important in a virtual environment. A user can benefit from intuitive methods and natural motions to interact with data and objects in immersive environments. For example, designing a Histogram with the same interactivity as flipping pages in a book and giving users natural motions to perform benefit the user experience. Along with intuitive and natural methods, interactions that utilize visualizations with a broader view of a data object benefits the user experience as well.

Studies such as [23] brought in data analytics experts to test their platform, however the benefit of IA can be seen in everyday people as well. Scenarios provided in [5] show that everyday biologists could benefit from VR immersive analysis. Bringing these technologies to everyday life require everyday techniques, which is why the utilization of a natural user experience in concurrence with immersion is key in immersive techniques. This isn't to say that no experts of any field cannot benefit from these innovations, such as doctors performing virtual colonoscopies that felt more natural than desktop applications [42]. A natural user experience in immersive environments can benefit the experts in their field as well as the everyday worker.

Delivering a natural user experience is imperative to platform design, as giving the user more freedom and flexibility to look at the data with actions they are familiar with can improve user experience in these platforms. For example, allowing the users to freely move a virtual data object in their hand to gain a better insight of the data gives the user a more natural experience (as if they were holding a real object) [41]. However, we can simulate this natural experience within the unnatural environment that is a virtual scene; creating floating menus that would be interacted with naturally, but otherwise would not be able to exist without simulation. Creating comfortable and efficient approaches to data exploration can increase the adoptability of immersive analytics applications [39][18].

Another important aspect of the natural user experience is the way the user interacts with the data. Utilizing a controller that may have unfamiliar button schematics or complicating controls can deter users from using an HMD. With the introduction of hand-tracking technology, such as the Leap Motion Controller, we can introduce natural hand-gesture motions to manipulate the data at hand with natural movements [37]. With the consideration of the interactions the user will perform on the data, mode of locomotion must also be considered. This study will encourage a different approach to see if movement/manipulation of a given dataset could be beneficial to a user if occlusion is present in a given dataset. There are instances where users can see every bit of data in front of them, but some cases where they may need to look around by rotating their body and head, physically navigating via walking, or virtually navigating via teleportation.

2.3 Leap Motion/Unity

The Leap Motion Controller is an infrared hand-tracking camera that typically attaches to the front of a VR HMD. Figure 1 shows a sample of how the controller works without using a VR HMD and how the controller translates the data it captures from the camera to the computer. Exploring the effectiveness of hand-tracking technology is important to consider when testing immersive analytics platforms, as increasing immersion and natural experience seem to benefit the user when exploring data. It remains to be known what possibilities come with using natural hand gestures with immersive technology [34]. Recognizing dynamic hand gestures with the Leap Motion Controller has been found to be effective; identifying specific finger extensions, touching fingers, and other detectors are available to craft intuitive hand-gesture controls [44].

Figure 1

Leap Motion Controller

Cross-platform game engines such as Unity can be used to support IA platforms. New applications for immersive devices come with more ease through these engines. The issue with developing virtual reality platforms and games during the 1990s is that much research focuses revolved around hardware development. Now, software can flourish as HMD can support more and more applications created on platforms like Unity [25] as seen in Figure 2. But games are not the only applications we can bring to VRHMDs.

Figure 2

Unity Game Development Engine
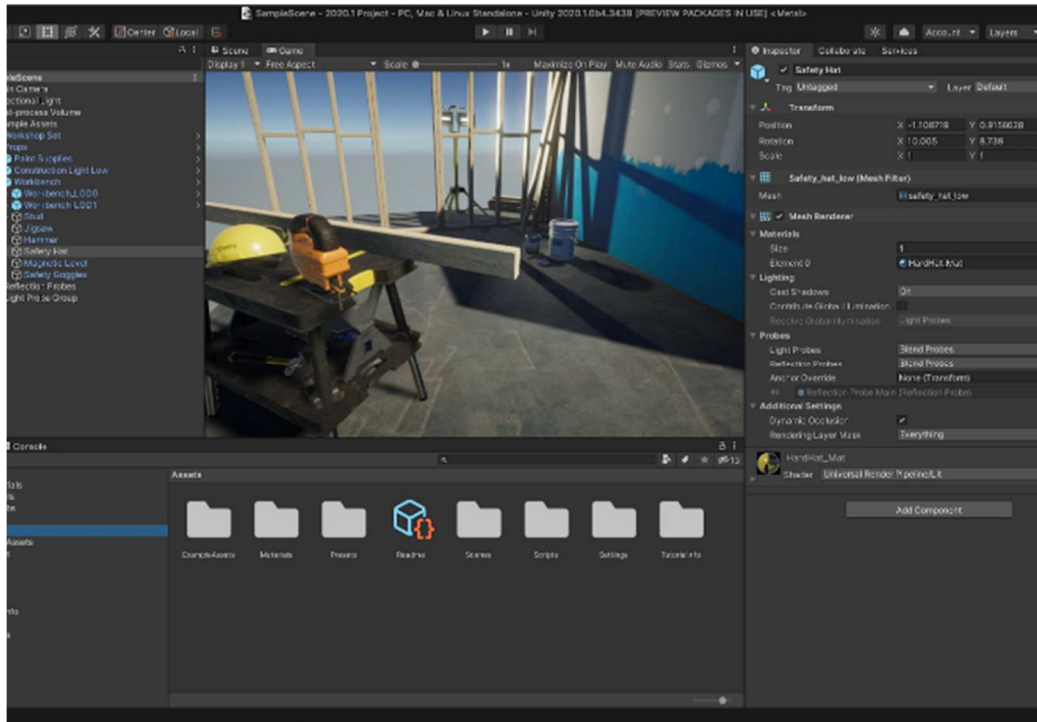
Applications can be developed for the real world on Unity that can be used with a VR HMD [43]. Together with the Leap Motion Controller, new innovations can be achieved. Neutron Scattering scientists have stated that they need more intuitive 3D visualization and analysis tools that provide accessible interactions with large and complex data which could be benefitted using hand-tracking technology and the Unity game engine [9].

2.4 Virtual Reality (VR) Locomotion

Exploring each aspect of how a user can move about the virtual space, and how the user can interact with the virtual space are two important distinctions [21]. There are many ways to explore a virtual space and navigate the environment [12]. Physical navigation like walking depends on the size of a room or the given technology that can allow walking in a static space (like a moving floor pad). Teleportation, or traveling at infinite velocity, is another technique that can prove to be useful in confined spaces. Traveling mass distances in the virtual space with minimal effort and no extra physical space required can be a benefit to developers with limitations, however the effect of immersion by utilizing infinite velocity techniques could be taxing on users [22]. Establishing a clear backdrop is important when implementing infinite velocity techniques to improve the sense of presence after jumping, giving the user familiar surroundings to ground themselves in [10]. Gesture-based teleportation technologies have not widely been used [29][3]. Controller-based teleportation has proven to be more successful than gaze-based teleportation, so exploring the natural user experience with hand-gesture technology is important to note. Techniques such as standing in place and rotating around an immediate environment may not classify as locomotion, however the movement and interaction are explored in this study [28][1].

2.5 Spatial Ability

Measuring the spatial ability of a user before using a VRHMD application is a notable aspect of virtual environments. Virtual reality increases the attentiveness of participants and lowers distractions, however seeing which users may have a better spatial grasp beforehand could prove beneficial [17]. According to [7] those who scored higher on their mental rotation test, like the spatial ability test administered in this study, could perform more efficiently on data detection.

2.6 Occlusion

A problem with 3D data visualization, as well as the hand-tracking technology of the Leap Motion Controller, is the issue of occlusion. This may refer to objects standing in the way of viewing another, which is why movement or manipulation within a virtual space is important to establish in some manner [15]. However, within a virtual space we could limit the amount of occlusion a user experiences by giving a less-crowded, more digestible view for the user [2]. Since navigation is important to encourage in some aspects of virtual reality, occlusion can be used as a natural way to guide users through certain scenes of data [32]. But it is important to note that giving users the option to bypass these occlusions for faster viewing of the data should be available [46].

The Leap Motion Controller itself is a victim of occlusion, as the front facing camera cannot detect hand movement if there is an object between the camera and the

hand, or if the hands are not in view at all [7]. For example, a user that points straight out in front of them may experience occlusion with the hand-tracking technology. The user's finger may curl down or act strangely; this is because the user's hand is blocking the view of the camera from seeing the pointing finger, which to the Leap Motion Controller it assumes the user's hand is closed since it cannot see the finger.

As previously stated, adding more personalization to the user's virtual avatar could benefit the user experience and increase immersion. However, bringing too much reality to virtual reality could hinder performance. According to [27] adding virtual arms can block users from viewing the data, adding to the occlusive elements of the scene. The use of Leap Motion in this case is beneficial since only the hands are virtualized when creating a platform in Unity with Leap Motion.

Chapter 3

Methodology

3.1 Design Considerations

In order to fully understand what methods are most effective in immersive analytics, different viewpoints and modes of locomotion must be considered. 3D User Interaction (3DUI) for immersive analytics is a new field which requires guided principles in several design settings to explore its effectiveness. With this, we introduce two modes of interactivity between the subject and the data in concurrence with three different modes of locomotion for the subject to navigate the virtual environment.

3.1.1 Mode of Interactivity

With a virtual environment we can enhance the user experience through the level of immersion which comes with two different viewpoints; a godlike position manipulating and viewing data points from above or plunging the user within the data itself to enhance immersive experiences. These two viewpoints are the Bird's Eye View, looking from above in an aerial view as seen in Figure 3. And the Grounded View, walking among the data points as if it were the natural environment around them as seen in Figure 4. Subjects are tested under these two modes of interactivity.

Figure 3

Bird's Eye View Interactivity Mode
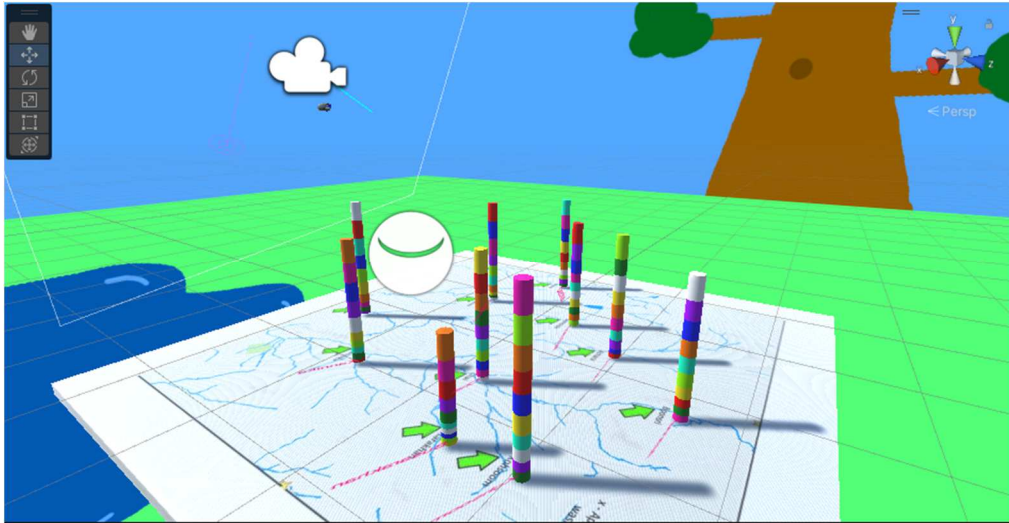
Figure 4

Grounded View Interactivity Mode
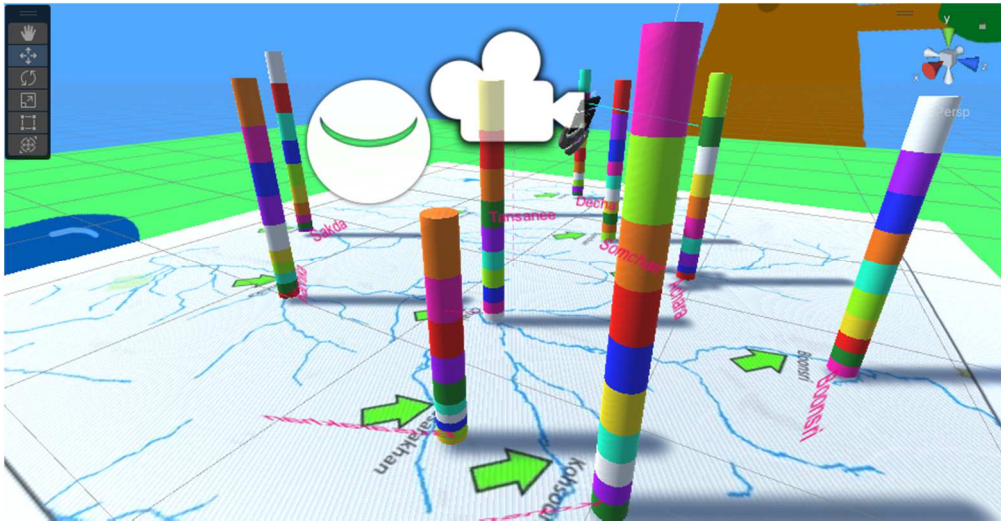
3.1.2 Mode of Locomotion

Along with the two modes of interactivity, another aspect of virtual immersion is to be considered; the way users move around in the virtual environment is important as natural movement could enhance the sense of immersion. To test this, six different design settings are created: three bird's eye view simulations and three grounded view simulations. Each simulation is of a different view but dictates three different ways the user physically or naturally moves about the virtual space. Combined with the mode of interactivity, the different modes of locomotion tested in the virtual environment are sitting/stillness, walking, and teleportation. In each mode of locomotion participants are questioned through visual confirmation and are either given hand gestures or the ability to walk and physically navigate the room in order to manipulate the data. Participants would complete the three simulations that differ the modes of locomotion based on the mode of interactivity they are assigned to. Table 1 outlines the composition of each simulation that each participant will go through based on the assigned interactivity mode.

Table 1

Effective Immersive Analytics for Everyday Use; Simulation Composition

Interactivity Mode	Mode of Locomotion	Answer Confirmation	Data Navigation
Bird's Eye View	Sitting/ Stillness	Visual	Hand Gesture
Bird's Eye View	Walking	Visual	Physical Navigation (Physical Walking)
Bird's Eye View	Teleporting	Visual	Hand Gesture
Grounded View	Sitting/ Stillness	Visual	Physical Navigation (Pivoting/Physical Rotation)
Grounded View	Walking	Visual	Physical Navigation (Physical Walking)
Grounded View	Teleporting	Visual	Hand Gesture

3.2 Cube Score Test

The spatial ability test that was conducted from Ekstrom [9] is a cognitive test that measures the spatial awareness of an individual, referred to as the cube score test. Figure 5 shows a sample of the description within the Ekstrom Cube Test. The implemented test labeled S-2 asked participants to identify the pairs of die listed as the same or different. Each question had two dice that showed three different faces, both turned in certain ways. Although it's possible for some dice to be the same, there are instances in which there is no possible way that the two dice shown can be the same given there are no duplicate

faces in the given dice. Therefore, if it's possible to be similar then the participant would guess 'same'. If the dice cannot be the same, they would guess 'different'. This test was adopted to see if an individual's spatial ability has any correlation with participant performance within an immersive environment. By gauging the general spatial ability of a user, observations can be made on how to better suit an environment based on whether spatial ability truly affects how an individual interacts within said environment. Figure 6 shows the sample of what participants saw during their spatial ability assessment. Comparing these results with participant question time can help tell

whether this spatial awareness can be beneficial to a user. This can also tell how to model an environment to compensate for those who do not have such spatial awareness. These findings can help the field of immersive analytics with efficient user design.

Figure 5

Ekstrom Cube Test

CUBE COMPARISONS TEST -- S-2 (Rev.)

Wooden blocks such as children play with are often cubical with a different
letter, number, or symbol on each of the six faces (top, bottom, four sides).
Each problem in this test consists of drawings of pairs of cubes or blocks of
this kind. Remember, there is a different design, number, or letter on each
face of a given cube or block. Compare the two cubes in each pair below.

Figure 6

Performed Spatial Ability Cube Score Test
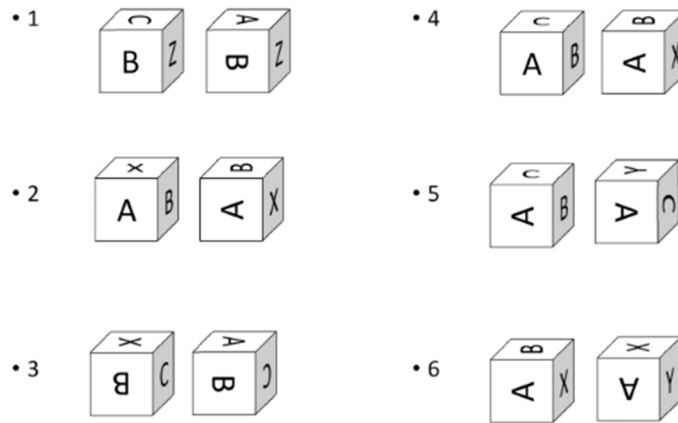
3.3 Immersive Workspace

The virtual reality test conducted in the immersive workspace consisted of multiple simulations that the participant would go through. These simulations are designed in a way to test the different ways people can move and interact with the data and environment.

3.3.1 Experimental Design

3.3.1.1 Environment. The environment around the participant resembles the fabricated nature preserve given in the 2018 VAST Challenge [10]. Figure 7 shows an overall view of the map within the environment that the participants will be gathering their information. In some simulations the map represented a table to walk around, in

some the map itself represented the ground to walk on. To reduce disorientation, major

landmarks are placed in the background of every simulated environment. In each cardinal

direction depicted a different, clearly identifiable landmark: a house, a tree, a mountain,

and a lake, as shown in Figure 8. Above is a blue sky with clouds and a sun, below is a

solid green landscape. This clearly defined environment is designed to ensure participants

do not become disoriented when performing actions such as turning in place, teleporting,

or manipulating the rotation of the map if able.

Figure 7

VAST 2018 Challenge Boonsong Lekagul Nature Preserve
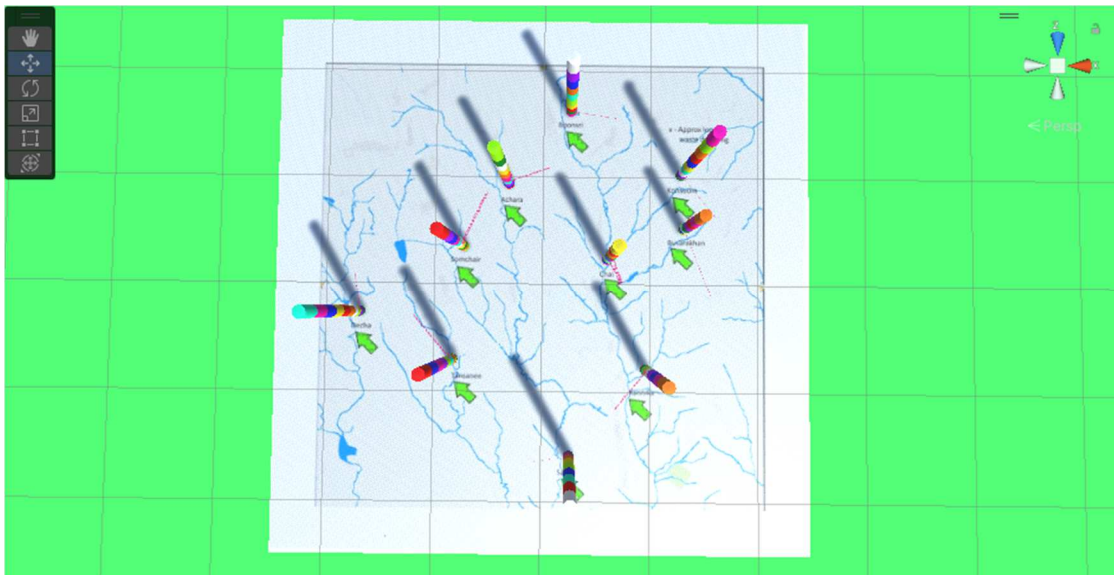
Figure 8

Simulation Skybox Landmarks

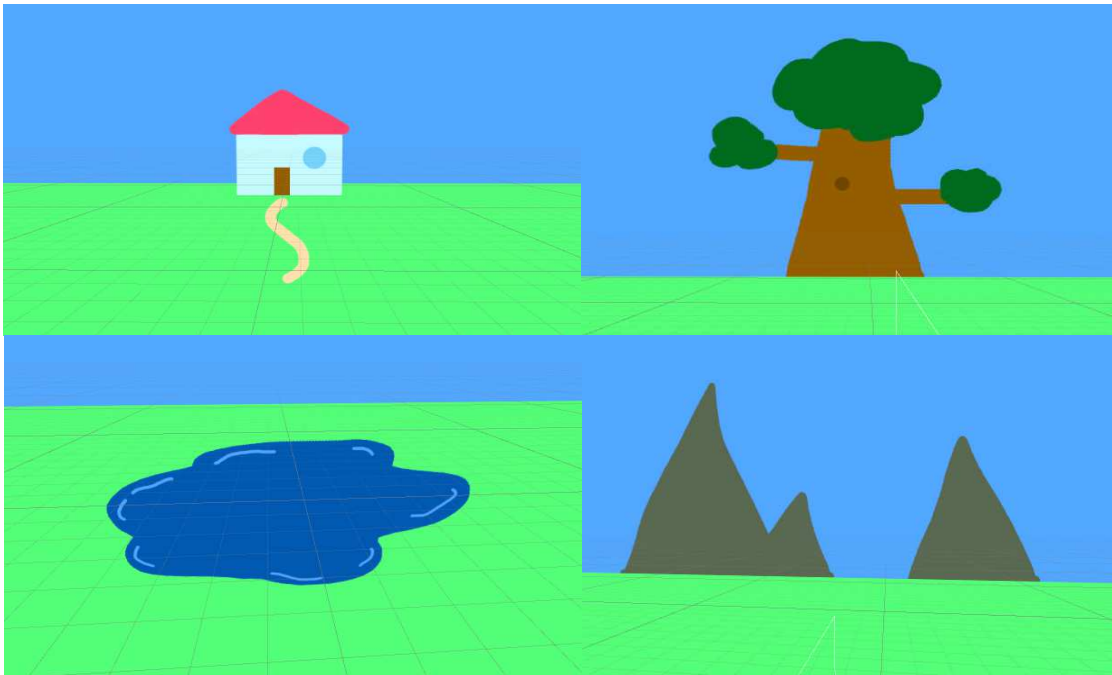**3.3.1.2 Dataset.** The platform is modeled after the aforementioned dataset, but the exact measurements were not used since the study focuses on the 3DUI design principles and the interaction design, not data analytics aspect of the challenge. Each location on the map is represented by a column of multi-colored segments. Each segment represents a different chemical tested in that given location. Figure 9 displays an example simulation where data is populating the map. Figure 10 shows two isolated data columns, which of each is a stacked column of segments that represents the tests done in that location in the given year. Chemical testing was performed over the course of 19 years and the date ranges from 1998 to 2016. There are a total of ten locations within the nature preserve, and ten different chemicals in total were tested and values were recorded. Each location name is printed at the bottom of the column; the first letter of each location is

capitalized and extends out to the right of each column and will follow the sight of the

user so as to not confuse the user as to where each location is placed.

Figure 9

*Simulation Dataset Example*
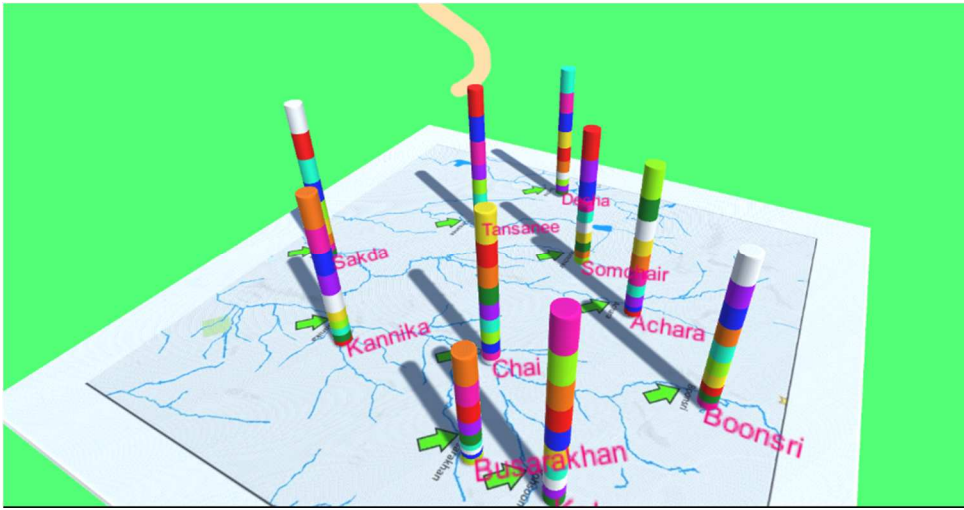
Figure 10

Simulation Data Column

3.3.1.3 Hand Gestures. When the participants focus their gaze on a specific name of a chemical, the value that pertains to it appears in text in front of the segment as shown in Figure 11. To help participants focus their gaze, a virtual crosshair is cemented to the view of the user in a distance away from the gaze as seen in Figure 12. This way, users can line up their gaze to face the segment, as everyone is different in judging where their eyes are placed versus their head. The user's head and eyes must be in line to trigger the information to display, henceforth the crosshair was provided as a reference. In some simulations where the user is encouraged to navigate the space physically or virtually, the crosshair is removed to encourage users to traverse closer to the columns to view the data. Figure 13 shows the difference with using a crosshair and being without one.

Figure 11

Data Segment Gaze Information
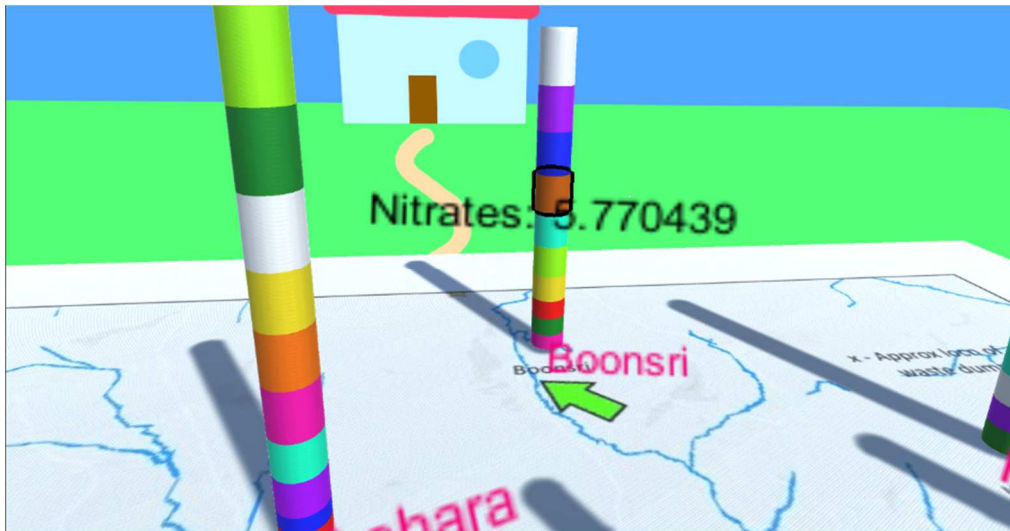
Figure 12

Virtual Crosshair
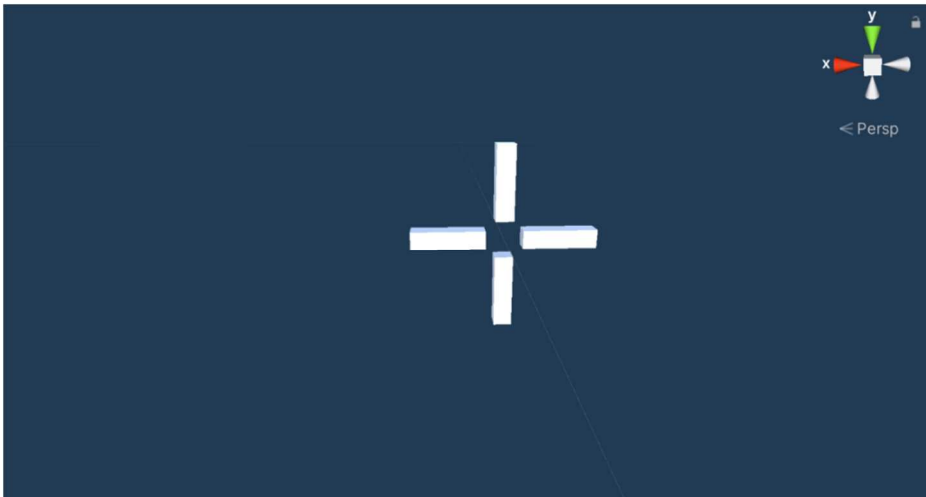
Figure 13

Participant View with/without Crosshair
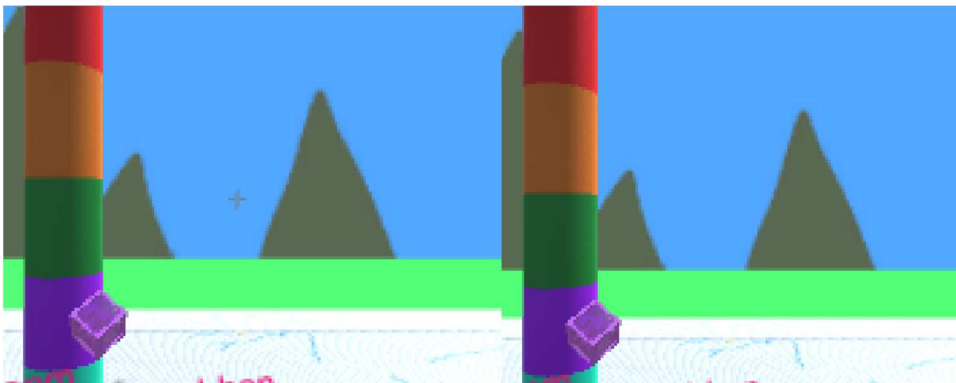
A number of hand gestures were implemented in order to manipulate the dataset. This was chosen over the use of virtual reality controllers to bring natural movement to participants in virtual environments. To do this, the Leap Motion Controller [11] is utilized for the hand- tracking technology. Along with Unity and the Leap Motion Development Package [12,13] the hand-tracking controller can be utilized within a Unity

environment. The Leap Motion core assets allows the Unity environment to work with

C# code to participants' hands.

    When describing the gestures to participants, the participants were told gestures are

best used when the hands are in front of the view of the camera, or directly in front of the

gaze, as if to push a door or place the hands on a wall. These movements include sticking

up certain fingers, rotating the wrist, or pointing a finger in each direction. Figure 14

shows the Unity script which controls the finger detection in the simulations. Figure 15

shows the Unity script which controls pinch detection in the simulations. Figure 16

shows the Unity script which controls palm direction detection in the simulations. The

following sections outline the gestures that are included in the test.

Figure 14

Leap Motion Finger Detector Script in Unity
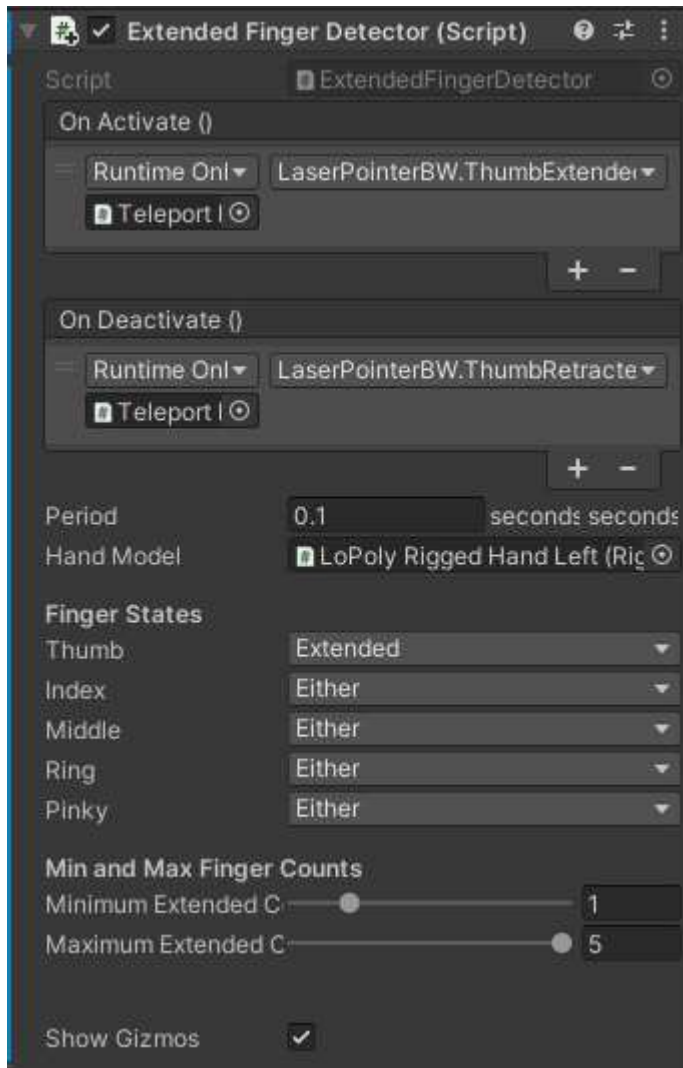
Figure 15

Leap Motion Pinch Detector Script in Unity
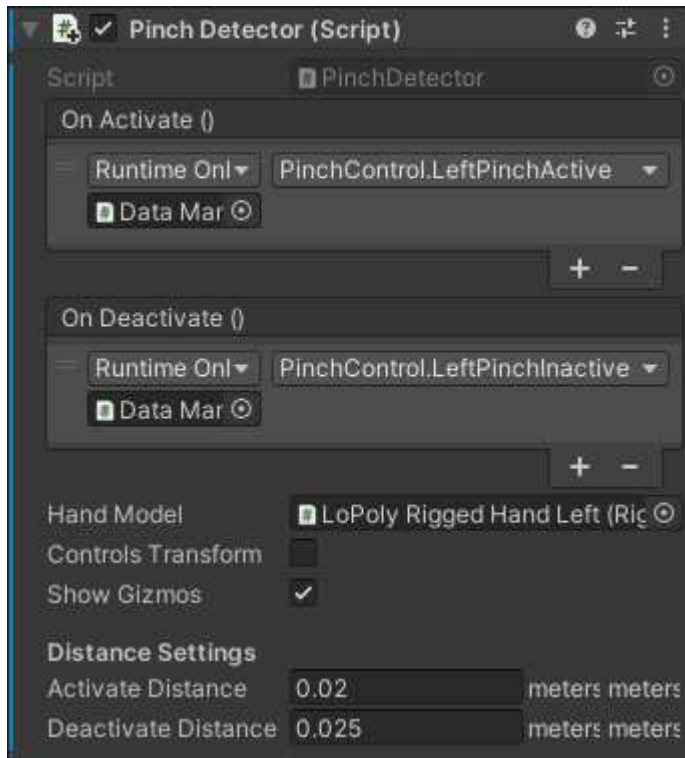
Figure 16

Leap Motion Palm Detector Script in Unity
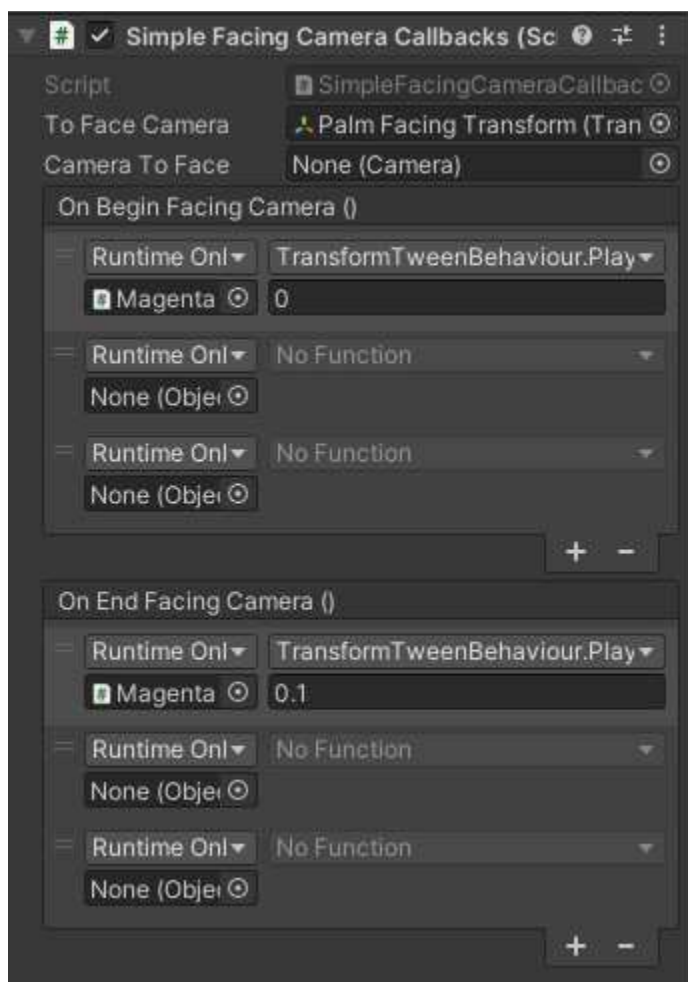
    3.3.1.3.1 Save Gesture. The Save Gesture copies the information from a given

chemical segment and pastes it onto the right hand. Figure 17 shows an example of the

virtual hand with a piece of copied information. The right hand has text information

attached to it, giving the year, location, chemical, and value of that chemical. Figure 18

shows the blank descriptive information on the hand when information has not yet been

saved. Different text will appear on the right hand when the gesture is performed, and

information is saved. To perform the gesture, the user must first have their gaze focused

on the chemical segment of interest. Then, with the right hand in view, perform the Save Gesture by extending the index and middle finger while keeping the rest of the fingers on the hand down. This resembles a peace-sign or a cub-scout salute with the fingers placed together.

Figure 17

User Hand with Saved Information
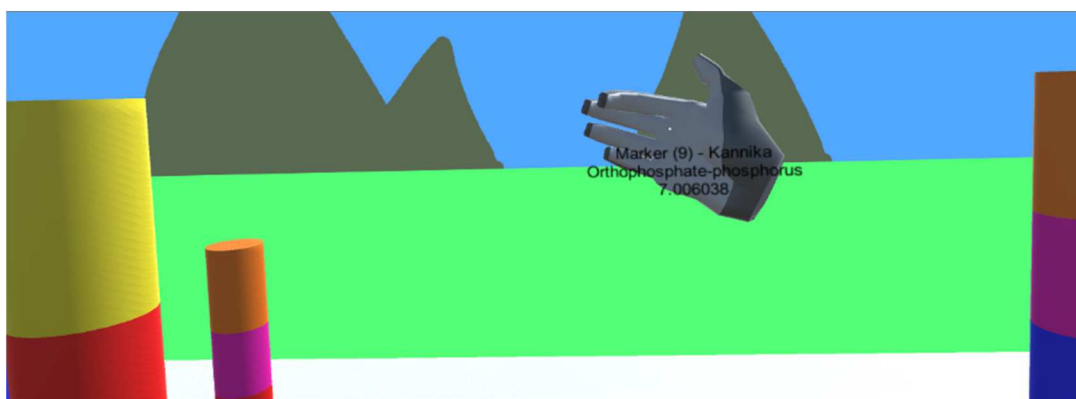
Figure 18

User Hand with no Saved Information
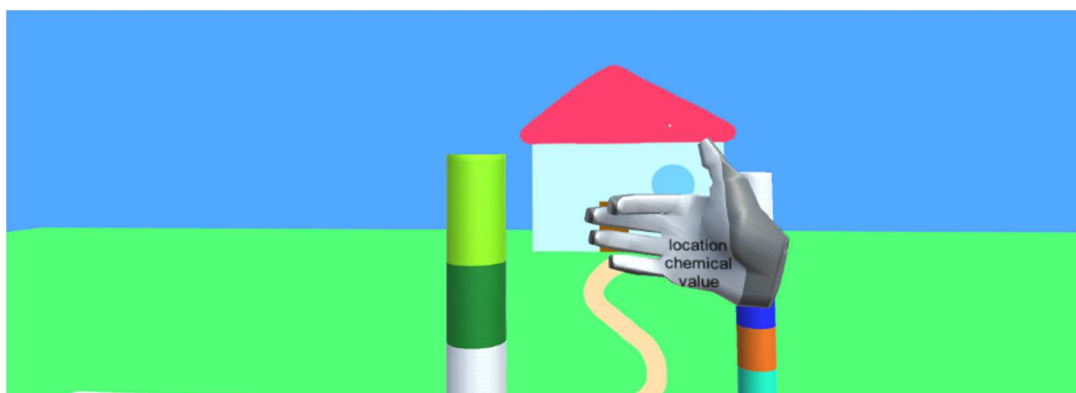
Figure 19 shows a demonstration of the gesture. The moment the gesture is performed, if the user is looking at a segment with the information displayed, that information is then copied onto the right hand. To ensure no information is accidentally saved and prevent overwriting, the participants are instructed to undo their right-hand gesture before looking away from the segment of interest. This way, the gesture will not activate if another segment is looked at with the information safely stored to the right hand. Figure 20 shows the Unity script for the save gesture where the save functionality is activated and deactivated based on the gesture performed. This functionality is available throughout all modes.

Figure 19

Information Save Hand Gesture
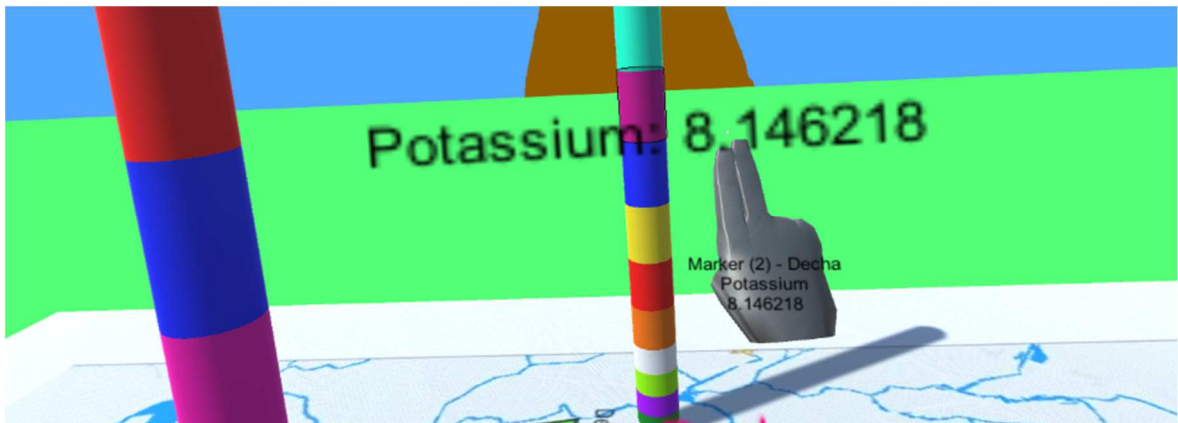
Figure 20

Unity Finger Detector Script for Information Save Gesture

3.3.1.3.2 Rotate Gesture. The Rotate Gesture rotates the map either clockwise or counterclockwise. The participants would rely on the gesture to change the view of the data in the sitting/stillness mod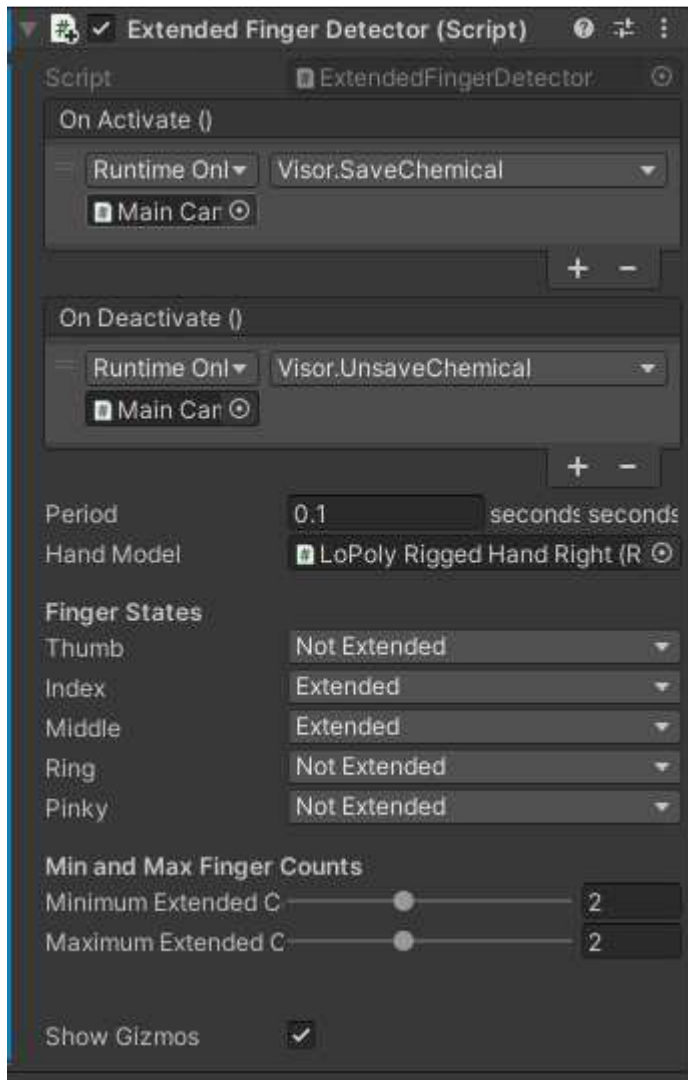e. To initiate this gesture, the user must extend the right hand into view and ball their hand into a fist, as if they were placing their fist against a wall. Once this is done, if the user extends their thumb out the map will begin to rotate as seen in Figure 21. If the user flips their wrist to point their thumb in the opposite direction, then the map will rotate in the opposite direction. This gesture functions with the invisible "horse blinds" on either side of the user which can be seen in Figure 22; when the fist is clenched and the thumb is extended, an invisible raytraced beam is cast. If that beam hits one of the blinds to the left or right of the user, the map will rotate accordingly. Figure 23 outlines the Unity script which controls this function. Note that the columns of the map and the name placements are not affected by this rotation. This functionality is only available in the BEV Sitting/Still mode.
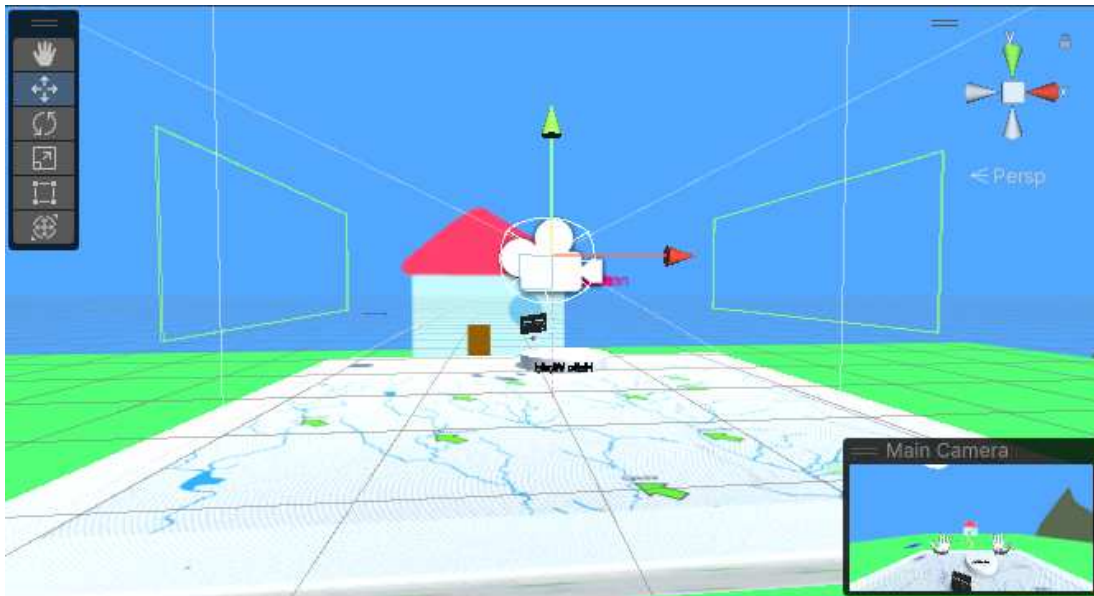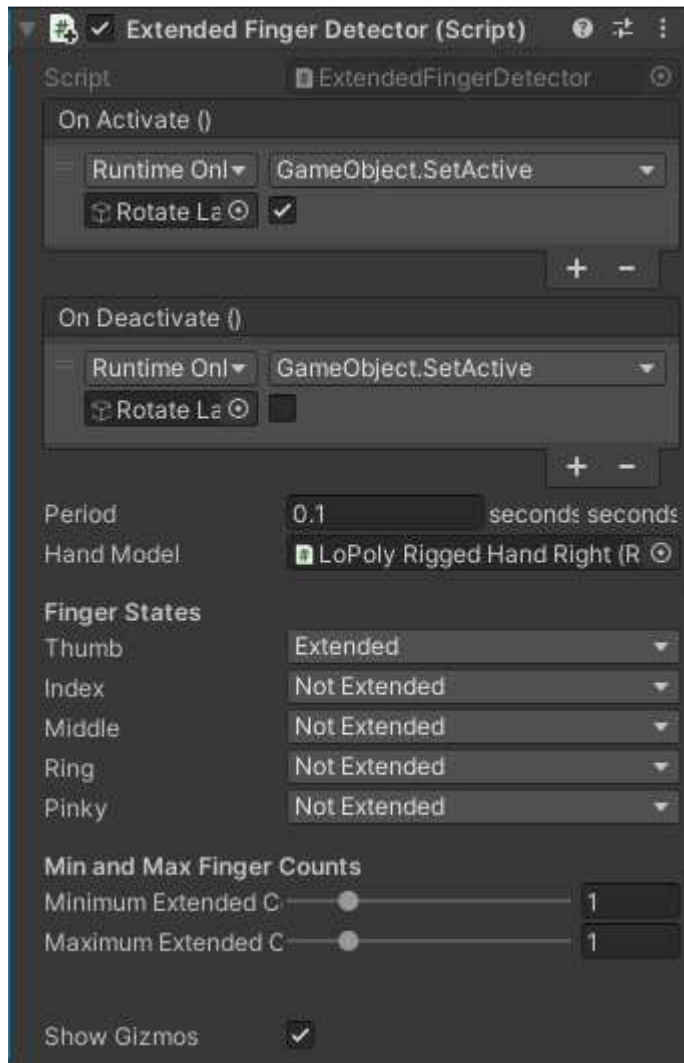
Figure 21

Rotation Hand Gesture
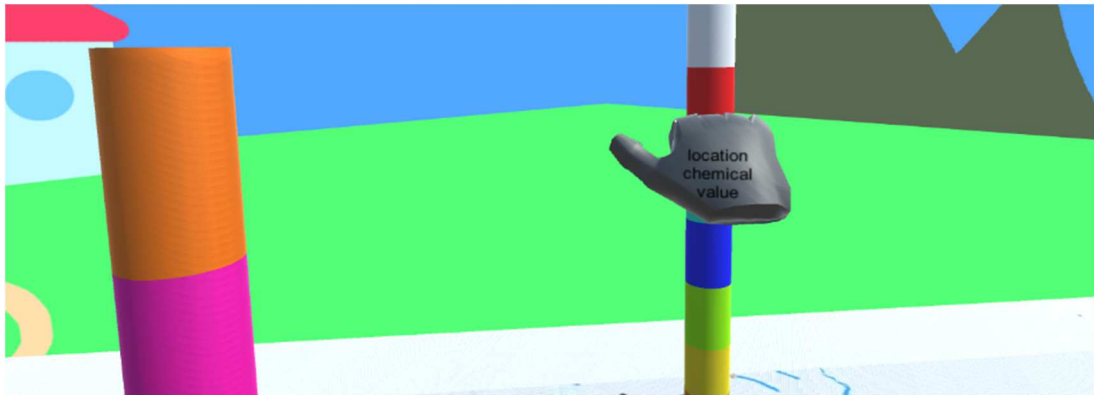
Figure 22

Unity Functionality of Rotation Hand Gesture

Figure 23

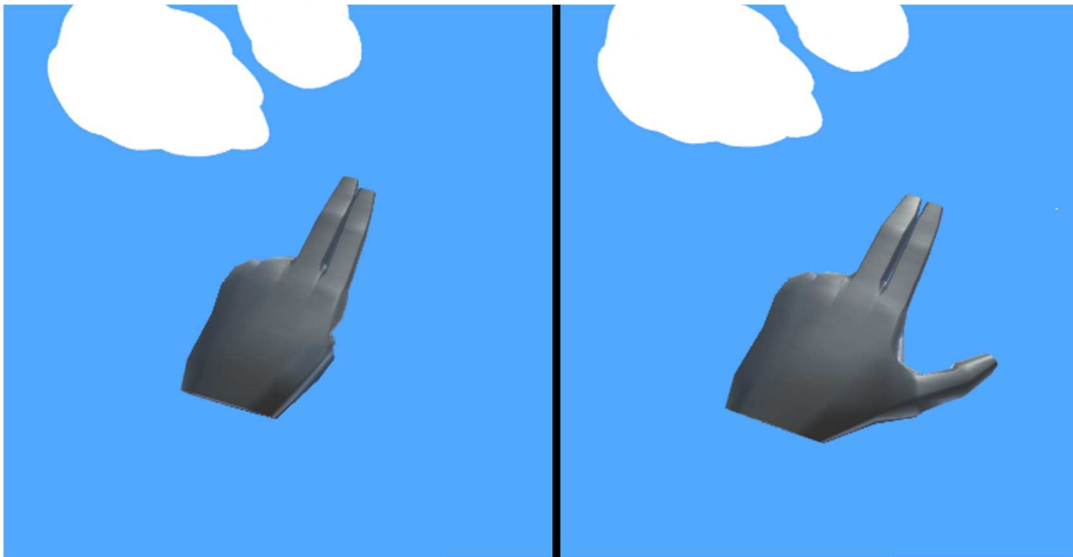*Unity Finger Detector Script for Rotate Gesture*

3.3.1.3.3 Teleport Gesture. The Teleport Gesture will cast an aiming beam on traversable ground and teleport the user to the location specified on the blue marker at the end of the beam. To initiate this gesture, the user must extend their left hand out as if they were pushing a door and to extend just their index and middle fingers (just as it is on the right hand with the Save Gesture). This can be seen in Figure 24. When this is done, a pink beam will be visibly cast to a blue marker along any ground that can be teleported to. If the user aims the beam off the map while holding the gesture, the beam will simply stick in place until it is cast onto ground that it can track. Figure 25 shows an example of a scene where the user is aiming the beam at the map below. The beam directs wherever the user's palm is facing, rather than pointing at a certain area. This is done due to the occlusive nature of the leap motion controller, as pointing directly would cause the user's finger to be occluded by their own hand. Once the user is satisfied with where they want to go, with the two index and middle fingers extended, the user must also extend the

thumb and hold. With this, in a few seconds, the user will jump to the location where the

blue marker lay. This gesture will not automatically reset and continue teleporting the

user, but rather they must undo the thumb and redo the gesture to teleport again. Figure

26 shows the Unity script responsible for controlling the gesture. This functionality is

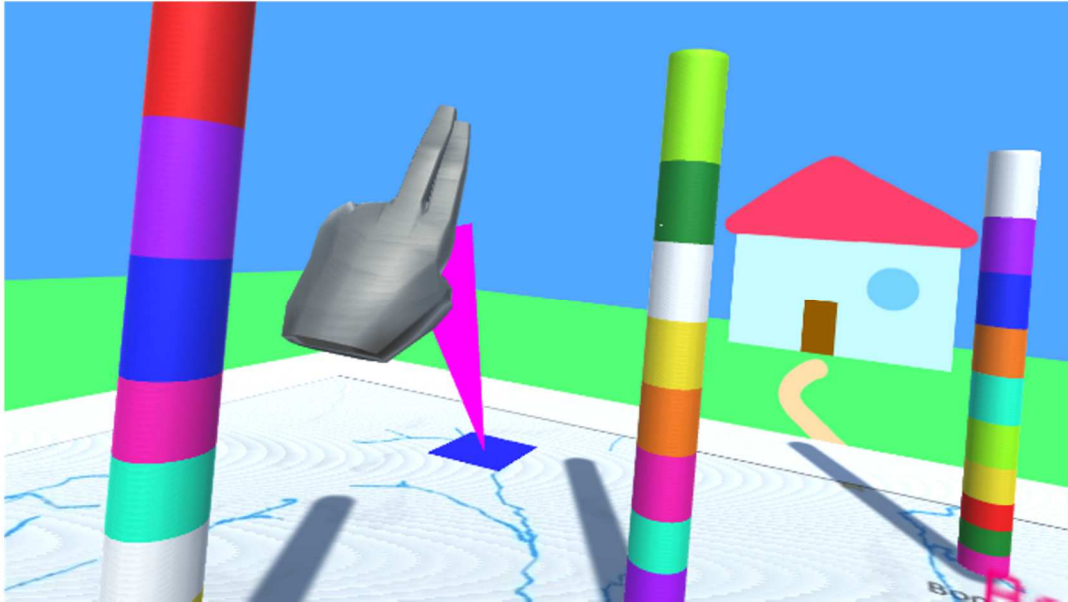only available in the Teleporting locomotive modes.

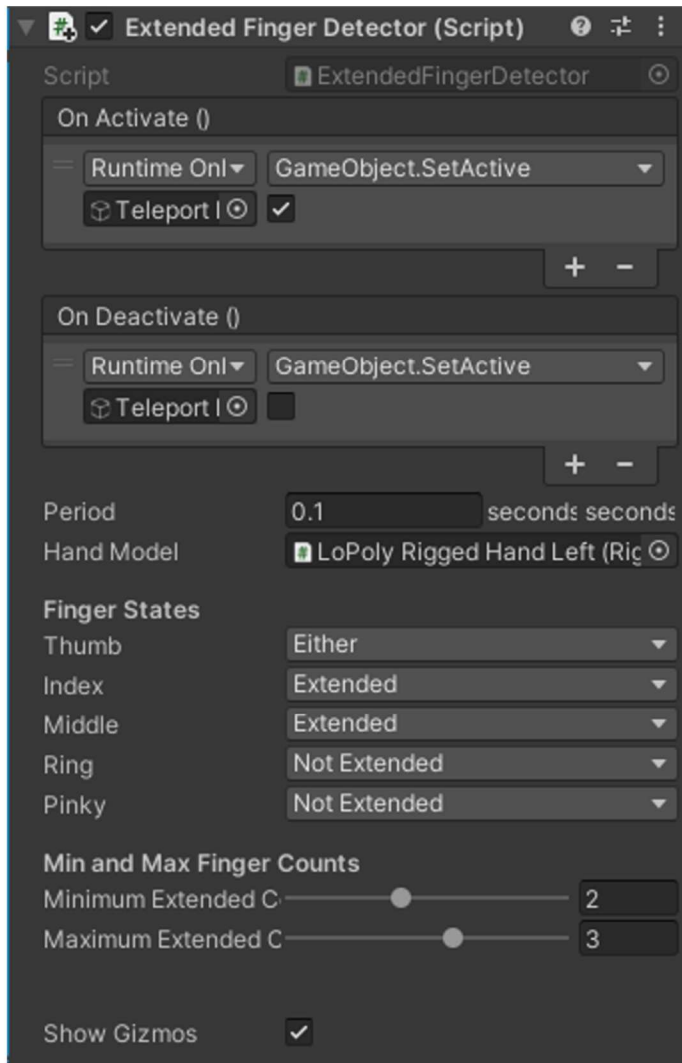**Figure 24**

Teleportation Hand Gesture

Figure 25

*Teleportation Aim Beam*

Figure 26

Unity Finger Detector Script for Teleportation Gesture

3.3.1.3.4 Resize Gesture. The Resize Gesture will continuously change the size of the map if the gesture is held. Figure 27 shows the Unity script that controls the resize gesture. To resize the map, both hands must be in view of the user's gaze. To initiate the size change, the user must touch their index finger and thumb together on each hand, as if to perform a pinch. Figure 28 shows this motion. This is what begins the resize function; while both hands are initiating in this pinch, the map will start to continuously change size. Nothing will seem to happen at first, but if the user takes their hands and brings them further from each other while performing the pinch, the map will start to grow. This is the same case for shrinking the map, bringing the hands closer together while pinching will cause the map to shrink. Figure 29 shows an example of an enlarged map vs. a shrunken one. The more the user brings their hands further or closer together based on the distance of the initial pinch, will increase the rate of growing or shrinking. For example, if the hands are moved just a bit further from each other, the map may grow slowly. If extended further the map will grow at an increasingly fast rate. To increase the flexibility of using this tool in conjunction with the rotate feature, users can invert the map by shrinking the size to less than zero. In this outcome, a gesture that would normally shrink the map will appear to make it grow and vice versa. To go back to a non-inverted view, just increase the size of the map until it switches. Note that this feature does not alter the size of the columns on the map, but simply brings them further apart or closer together. This functionality is only available in the BEV Sitting/Still mode.
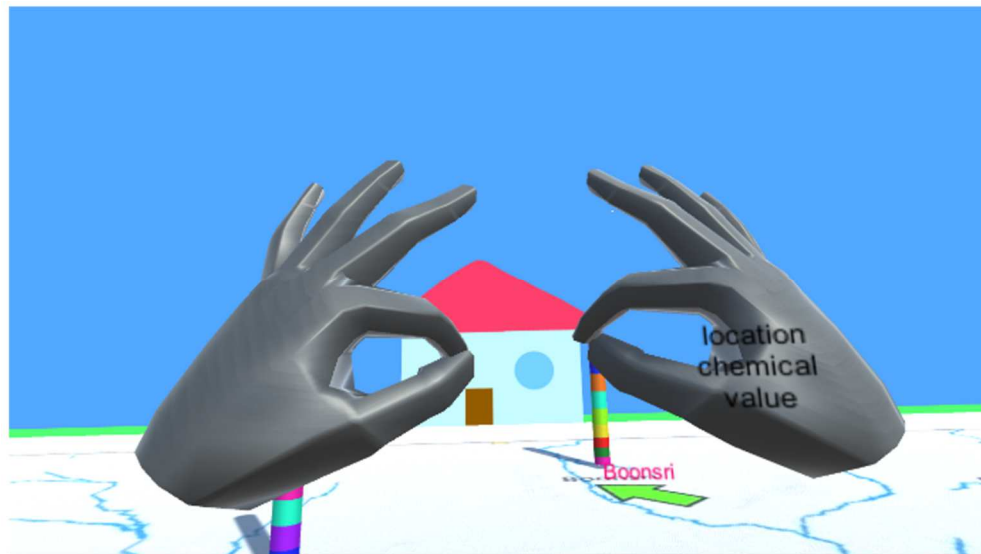
Figure 27

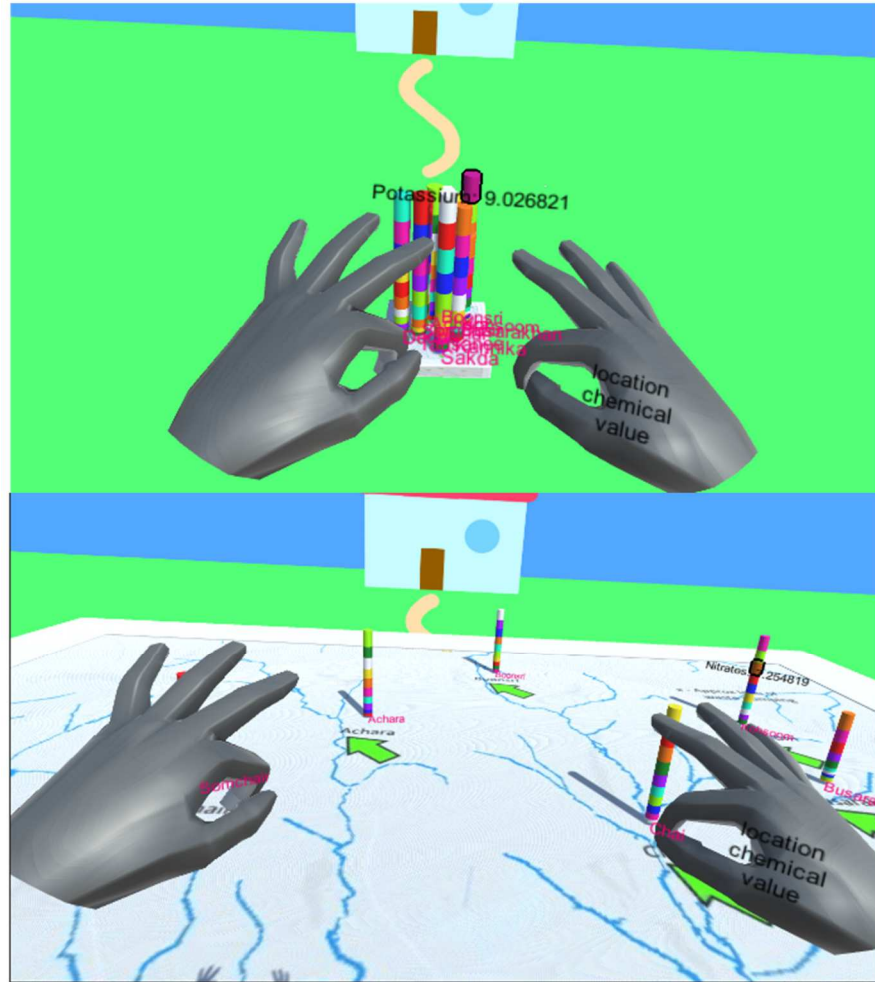*Unity Finger Detector Script for Resize Gesture*
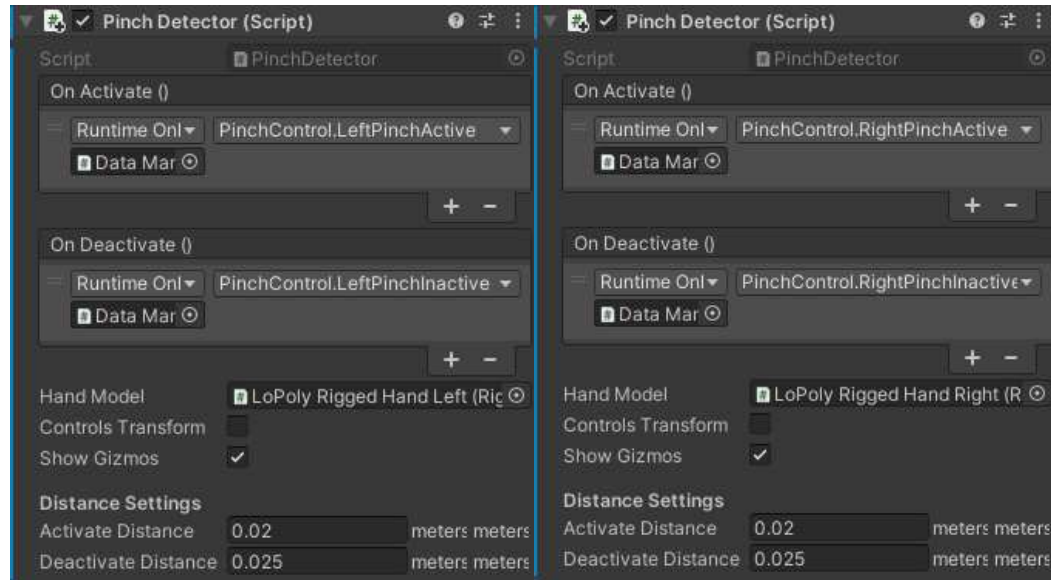
Figure 28

*Resize Hand Gesture*

Figure 29

Small Map Compared to Large Map

3.3.1.3.5 Control Panel and Scaling Time. The Control Panel is a workbench

that can be used when the user faces their left palm towards their face. Figure 30 shows

an example of the control panel within the scene simulation. Once this action is

performed, a control panel will appear with several features to the right of the left hand.

The first feature at the top is the time slider, which is used to change the time. Below that

is a legend of every chemical and the color that corresponds to it. At the very bottom is a

pink cube within a pink-colored wireframe box which acts as the control panel's anchor.

The user can press in on the button on the slider and drag it along to change the year as

shown in Figure 31. It is set to 2008 by default, and ranges from 1998 to 2016. The users

are advised to use an open palm with their index or middle finger to operate the time

slider, since the control panel itself can be entirely removed. If the user grabs the pink

cube at the bottom, or the panel itself, the user can bring the control panel away from the

left hand and place it in the virtual space in front of them. The control panel will stay in

place facing the user, even if thrown it will affix itself to a short distance from the user

and always face them. Figure 32 shows the control panel separated from the user,

suspended in the space in front of the user. Since navigation is a large part of the study,

this control panel can be left behind. To place it back into the left hand, the user must

grab the pink cube on the control panel with their right hand and place it within the

wireframe cube attached to the left hand. Once this is done, the left hand can be rotated,

and the control panel is attached to the user again. This functionality is available
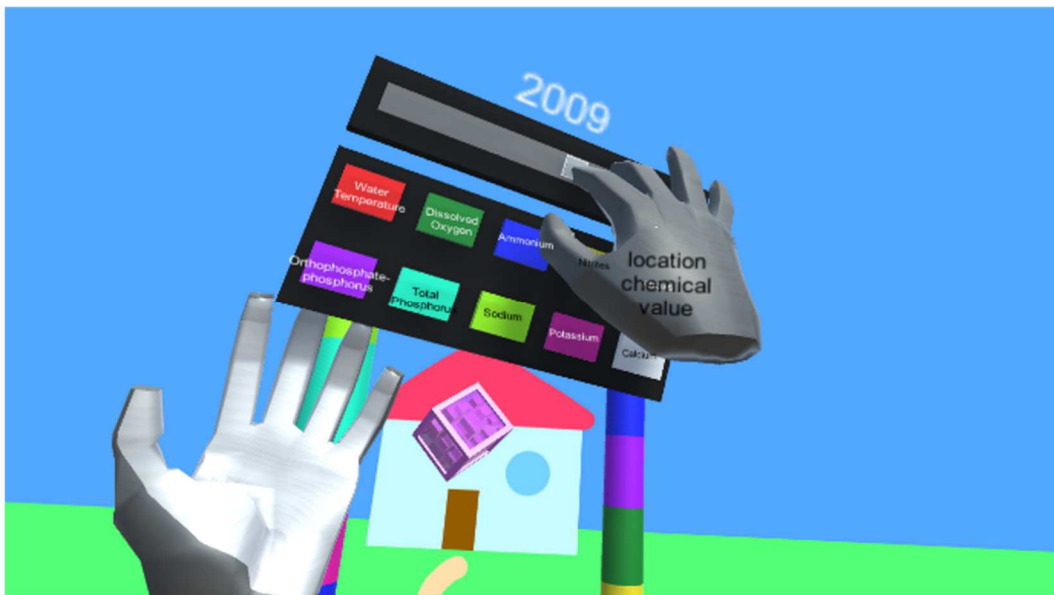
throughout every mode.

Figure 30

Control Panel
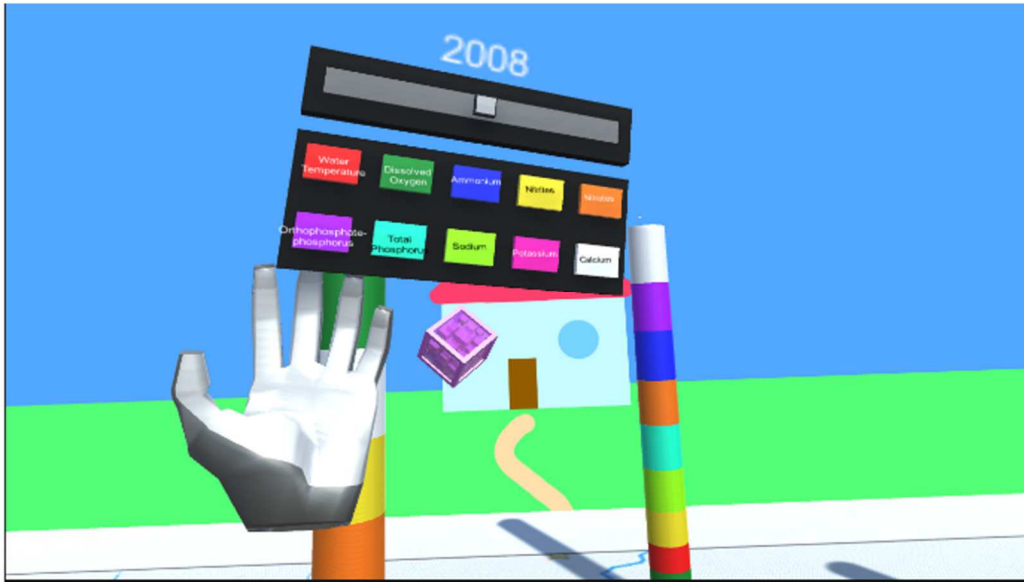
Figure 31

Changing Years in Simulation

Figure 32

Control Panel Unanchored
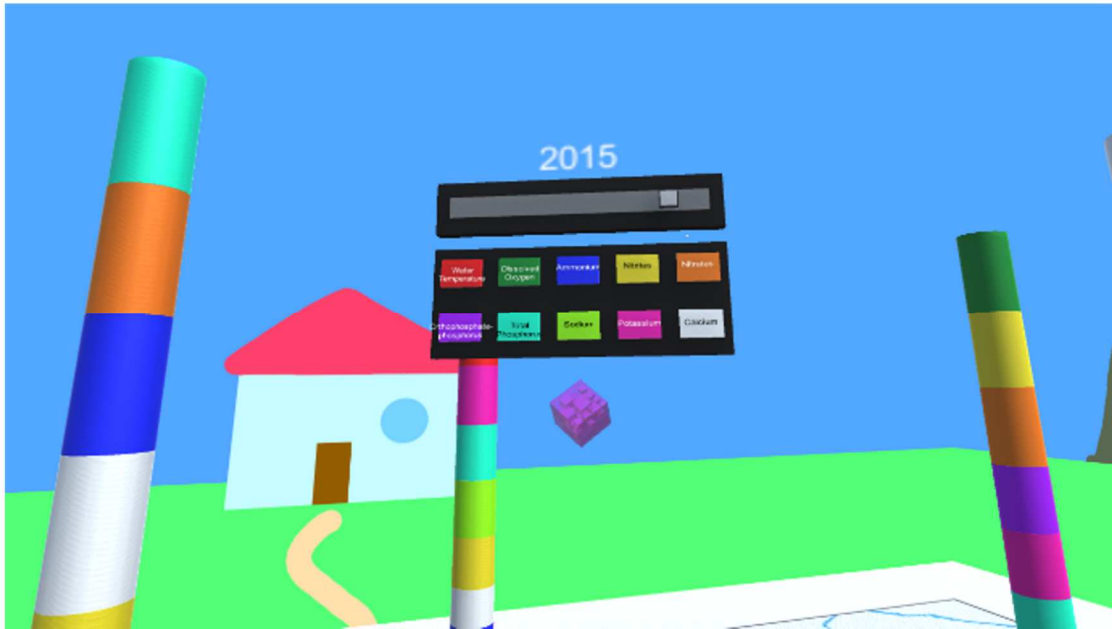
3.3.2 User Study Design

3.3.2.1 Tutorials. First, the participants are brought into a components scene where no observations would be held. Here, the participants would go over the functions and tools of the environment before conducting the test. Each participant was sent a video demonstration via email, however not every participant viewed the video. So, a short walkthrough between the user and investigator was conducted to show the participant how to use each tool. If the participant had any questions on how to use a tool or what gesture to perform, they are reminded as they are not required to memorize every single gesture provided in the immersive workspace.

3.3.2.2 Entry Survey. The first thing each participant completed was the entry survey. This was a series of questions just to gather information on the participant such as age, gender, and if they play video games or have experience with virtual reality. The final question is to assign their participant number to separate their information from the data we will collect.

3.3.2.3 Spatial Ability Test. Each participant took the spatial ability test on a laptop and was given the option to use the touchscreen, trackpad, or attached mouse to complete the test on Google Forms. The participants are told the instructions of the spatial ability test and given example explanations before moving on to the test. Once the test starts, the participants have one minute to answer the shown six questions at a time. Once participants completed the six questions, they would move on to the next set of six and the timer would restart. Participants are given warnings at thirty seconds and ten seconds on each set of questions. They are scored out of 42, the total number of questions, on how keen their sense of spatial ability was.

3.3.2.4 Component Scene. The first part of the virtual reality portion of the study is to run each participant through what they will be seeing and doing. In this Unity Scene called the Component Scene, every feature between the three simulations that they will be performing is available to use to practice here. The investigator gives a description of the environment and dataset to the participant and follows with explaining the hand gestures and having the participant practice these gestures. Once the participant confirms that they are done practicing and ready to begin the testing they move on to the beginning

of the observational test. Regardless of the mode of interactivity the participants perform,

they will run through the practice component scene to become familiar with the tool

before performing the test.

3.3.2.5 Simulation Scenes. The next part of the virtual reality test is the simulation

scenes. These scenes will follow the modes of locomotion within the participants'

respective mode of interactivity; so even though six separate scenes exist, each participant

will only be performing the test in three. The three modes of locomotion participants will

be utilizing are sitting/stillness; standing in place and rotating in one spot, walking;

physical navigation of a real-world room while in a virtual reality headset, and teleporting;

utilizing a hand gesture to navigate a virtual space. Each participant did not perform the

tests in the same order. This was done to randomize the data in case there is an aspect of

learning to the participants' performance. The tests are randomized in their order so that it

does not give users a specific advantage or disadvantage. These three modes of locomotion

are represented in different ways during the different simulations. In each of the simulation

images, the participant's position is represented by the camera icon in the figures, faded

or solid:

1. BEV Sitting/Still

In the Bird's Eye View (BEV) interactivity mode, the sitting/still locomotion, the

user is poised above the map as if it was angled like an easel. The user is able to look

down on this map and manipulate it via hand gestures with the Rotate and Resize

feature. The user is given a crosshair to accurately aim their gaze on chemical segments.

An example can be seen in Figure 33.

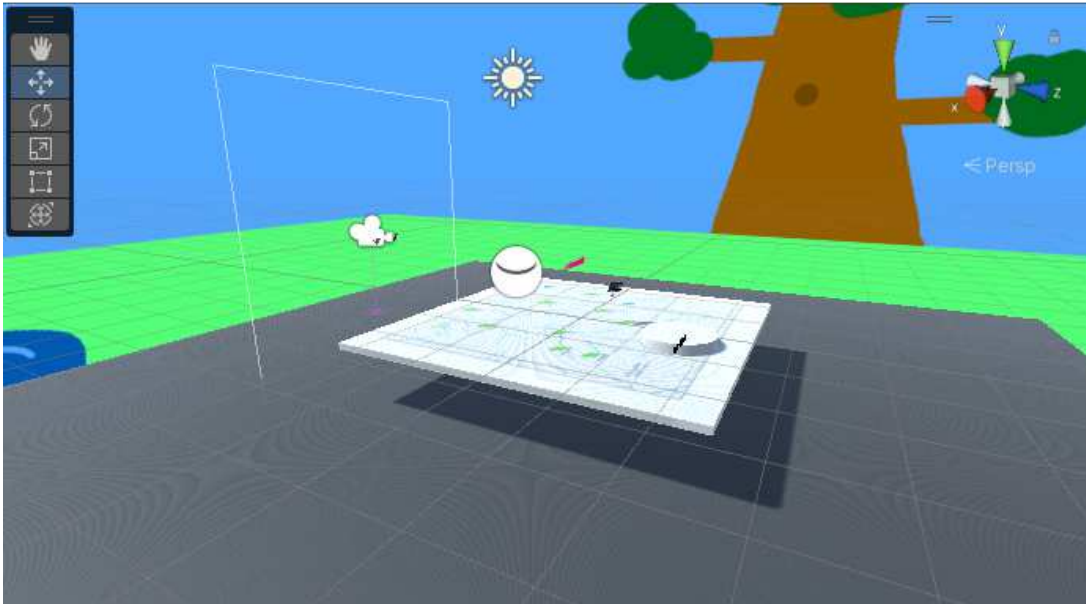**Figure 33**

Bird's Eye View Sitting/Still Simulation
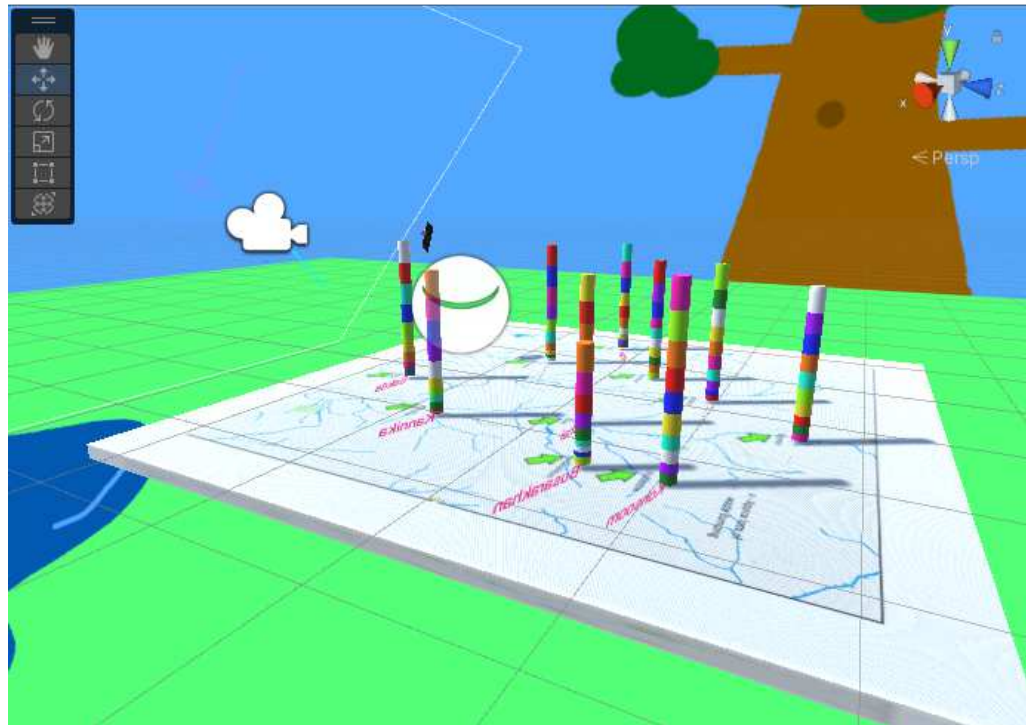
2. BEV Walking

In the BEV interactivity mode, the walking locomotion, the user is placed in a virtual environment where a table in the center has the map on top. The user is directed to physically navigate the walkable area around the virtual table without entering it and is given a crosshair to combat the table of occluded data points. An example can be seen in Figure 34.

**Figure 34**

Bird's Eye View Walking Simulation

3. BEV Teleporting

In the BEV interactivity mode, the teleporting locomotion, the user is placed in a

similar environment to the BEV Walking, where they are placed in a virtual environment

where a table is in the center that has the map. The user then is able to teleport around the

virtual table on the teleportable area around it. The user is not given a crosshair in this

situation to encourage users to get closer to the data points by teleporting around the

sides of the table. An example can be seen in Figure 35.

Figure 35

Bird's Eye View Teleporting Simulation
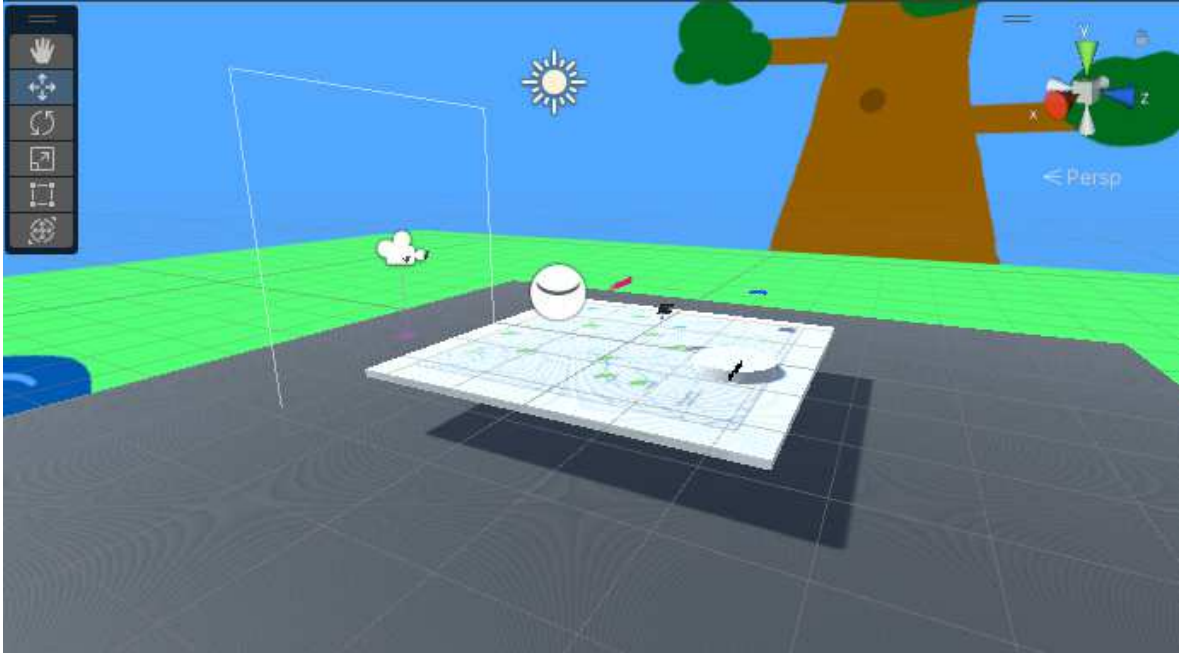
4. GV Sitting/Still

In the Grounded View (GV) interactivity mode, the sitting/still locomotion, the user is placed in the center of a virtual area where the map represents the ground, and the columns of data surround the user. The user is instructed to rotate in place and pivot, if need be, and a crosshair is given to the user to better aim their gaze. Figure 36 shows an example of the scene.

Figure 36

Grounded View Sitting/Still Simulation
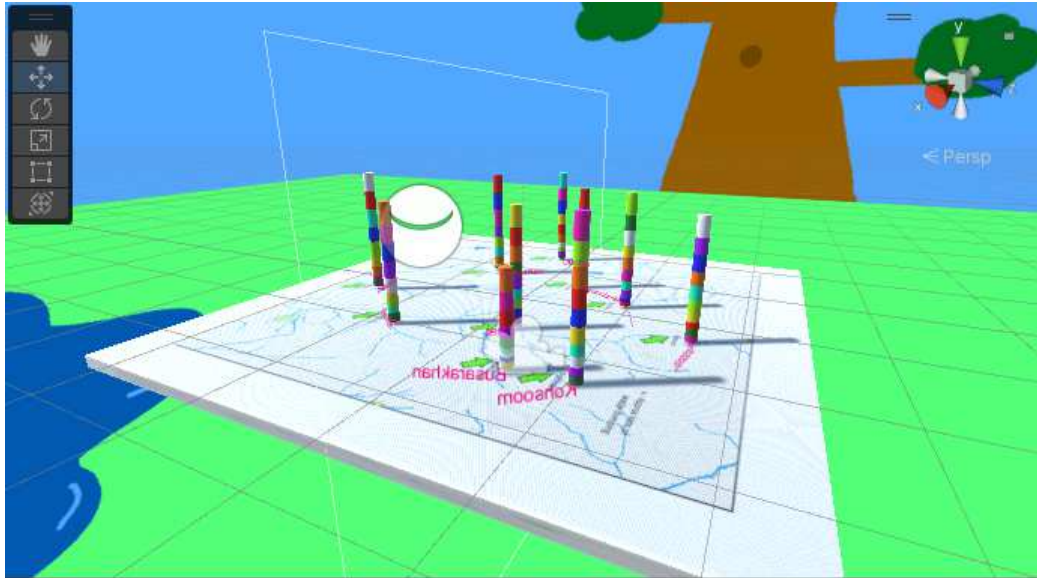
5. GV Walking

In the GV interactivity mode, the walking locomotion, the user is placed in a similar area as the GV Sitting/Still with the virtual area represented with the map as the ground. In this case the user is instructed to physically move about the area and is not given a crosshair to physically navigate closer to the data. Figure 37 shows an example of the scene.

Figure 37

*Grounded View Walking Simulation*
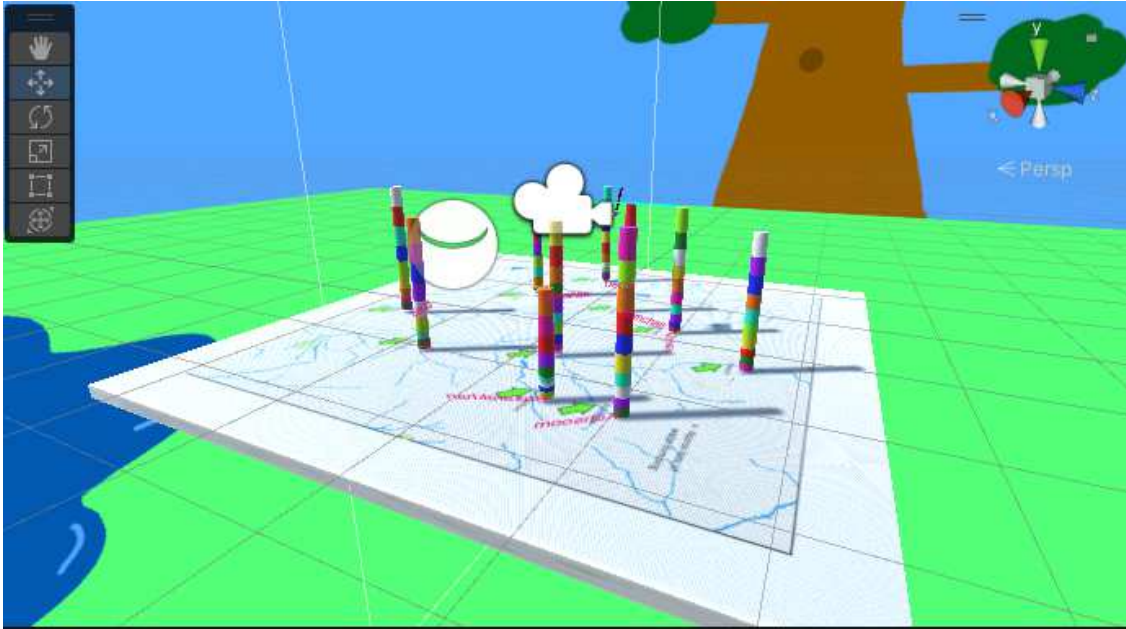
6. GV Teleporting

In the GV interactivity mode, the teleporting locomotion, the user is placed in an area with the ground represented by the map, however it is stretched over a large distance within the virtual space. Users are instructed to teleport around the map to get to each location of interest, and a crosshair is not included in the simulation to encourage users to teleport closer to the data points they wish to observe. Figure 38 shows an example of the described scene.

Figure 38

Grounded View Teleporting Simulation
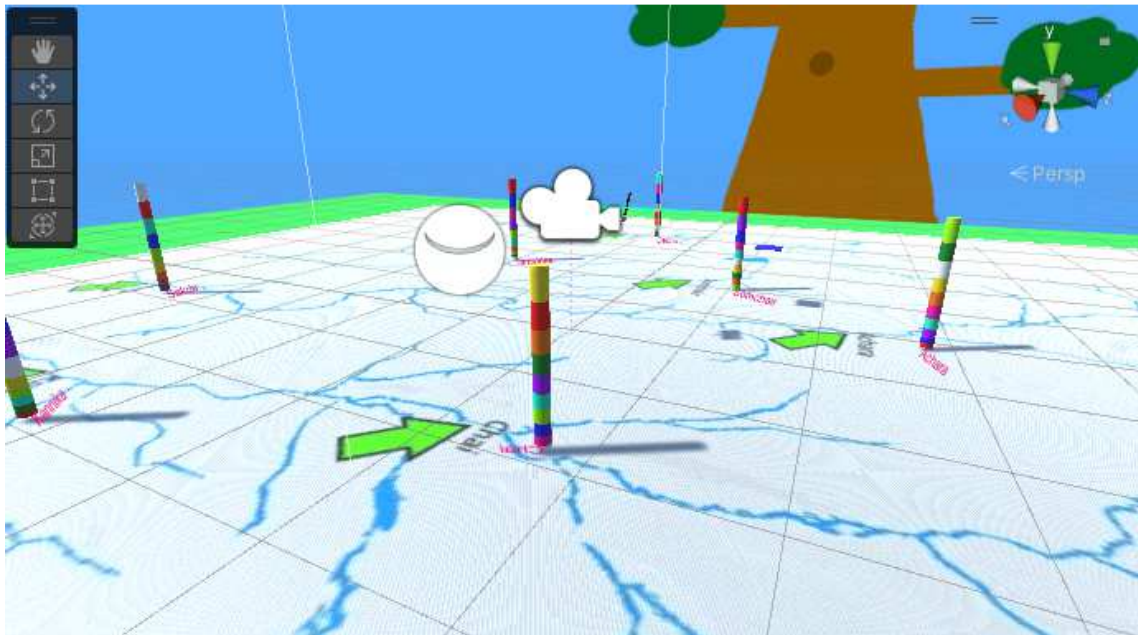
3.4 Questions

Each simulation shared questions based on each mode of locomotion. These questions were asked in order; however, the mode of locomotion order is switched per participant for randomization. The complexity of each question and how it may affect the time of finding the answer is as follows; first question: observe all data points in one year. Second question: compare two data points in one year. Third question: compare two data points in two years. Each question is asked as follows and any information from the question is repeated at the participant's request:

Sitting/Still

1. Which location has the highest level of Nitrates in 2012?

Kannika

2. Of the two, Decha and Kannika, which has a higher level of Ammonium in 2008?

    Decha

3. Which location and time have the higher value of Calcium? Sakda in 1999 or Chai in 2001?

    Sakda 1999

Walking

1. Which location has the highest level of Water Temperature in 2015?

    Decha

2. Of the two, Busarakhan and Tansanee, which has a higher level of Total Phosphorus in 2003?

    Busarakhan

3. Which location and time have the higher value of Potassium? Somchair in 2000 or Kohsoom in 2016?

    Kohsoom 2016

Teleporting

1. Which location has the highest level of Nitrites in 2007?

    Achara

2. Of the two, Somchair and Chai, which has a higher level of Dissolved Oxygen in 2010?

    Somchair

3. Which location and time have the higher value of Sodium? Boonsri in 2006 or Sakda in 2011?

Boonsri 2006

3.5 Exit Survey

After the testing is complete the participant is asked to fill out an exit survey asking for any comments or concerns of the tools, they spent time using. The exit survey then asks for the IM the participant performed as well as their participation number.

3.6 User Selection and Distribution

Testing different age groups and genders help us tell if certain demographics play any specific role in the effectiveness of an immersive analytics platform. The demographics were selected as follows; the age groups tested would be composed of two groups; of age individuals under, or over the age of 35, as well as both male and female participants. Both age and gender demographics make up large portions of the workforce and knowing if age plays any significant role within an immersive analytics platform for everyday use is key if added compensations to a given tool are necessary.

The distribution of participants is as follows.

<u>56 TOTAL PARTICIPANTS</u>

9 MALE PARTICIPANTS >35

21 MALE PARTICIPANTS 18<35

10 FEMALE PARTICIPANTS >35

16 FEMALE PARTICIPANTS 18<35

Table 2

Interactivity Mode Participant Distribution

IM	M>35	18<M<35	F<35	18<F<35
BEV	4	12	5	10
GV	5	9	5	6

3.7 Limitations

3.7.1 Oculus Rift

At first, it was considered to use the Oculus Rift S as the HMD (Head Mounted Display) of choice for a few reasons. One, it is a newer model of the previous Oculus Rift bringing clearer visuals, as well as not needing any external room setup for tracking. The cameras are placed directly on the headset of the Oculus Rift S, which makes setting up

boundaries in any room setting seamless. However, due to the technological limitations of the devices being used to perform this test, the only feasible headset that could be used was the Oculus Rift. This limitation brought two problems; One being that the room could not be easily tracked due to the camera setup of the Oculus Rift, two motion capturing cameras to be put on the table in front of your play area. This meant that if the cameras moved at all, the boundaries would have to be reset again. Compared to the Rift S, the original Rift's boundary mechanism is almost inoperable due to moving equipment in and out of the testing location. Not only that, but if the user moves too close to the camera setup, the Rift will begin to stop working.

3.7.2 Leap Motion Controller

The Leap Motion Controller proves to be an effective hand tracking device for its availability. However, the only time the hand may be tracked is if the hand is within the range of the camera. During the component scene of the case study, participants sometimes would have an issue with and persist with not keeping the hands in range of the camera. This could be due to tired arms, or just a difference in perspective with where a person is used to holding their hands away from their body for an extended amount of time. So, participants would try to perform hand gestures with their hands too far below the camera range or even at their sides, and nothing would occur within the simulation since the Leap Motion Controller could not detect the hand.

Figure 39

Leap Motion Controller Finger Occlusion
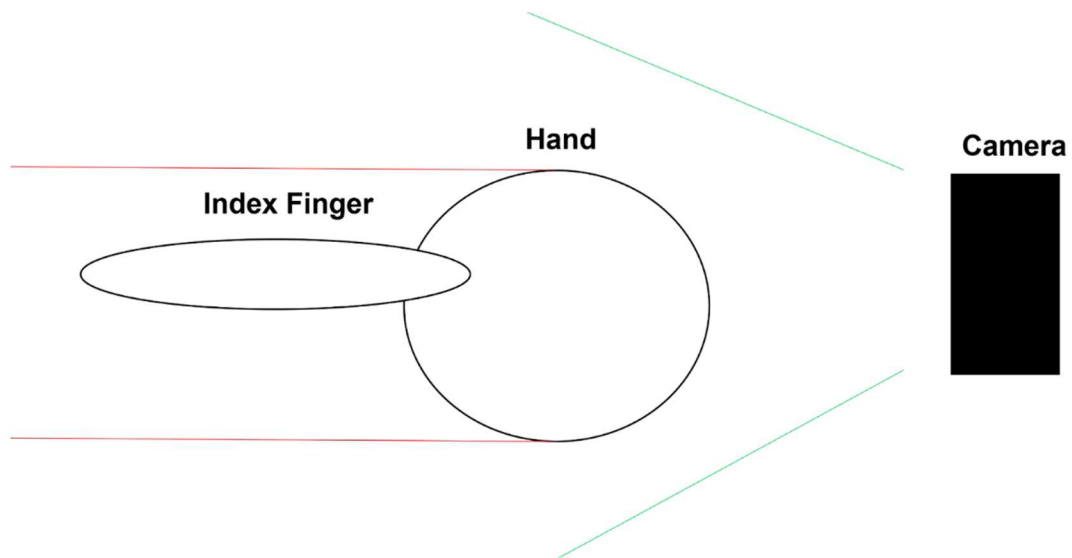
Another common issue with the leap motion controller is its problem with

occlusion. When the hand is not within range of the leap motion controller's camera, the

hand and finger movements cannot be tracked. However, say the participant pointed

straight out in front of them; their finger would curl down within the simulation, not stay

pointed outright. This is because the user's hand is occluding the camera's view from

seeing the position of the participant's finger. This was explained in the beginning of the

study to ensure users perform their hand gestures as if they were pushing a door, however

this limitation did take some getting used to with some participants.

Chapter 4

Results

4.1 Interactivity Mode, Locomotion Mode, and Question Analysis

According to Figure 57, between Bird's Eye View (BEV) and Grounded View (GV) within the Sitting/Still and Walking modes of locomotion, the GV interactivity mode is more efficient than the BEV interactivity mode in the second and third questions asked. Whereas, in the first question the BEV interactivity mode is more efficient that the GV interactivity mode. In comparison to this point looking at the Teleportation locomotion mode, the BEV interactivity mode is more efficient in every question over the GV interactivity mode.

The first question asks the user to review every location to efficiently find the answer to the question asked, to find the location with the highest value of a requested chemical. Across all three modes of locomotion, it is more efficient to view overall data points from a bird's eye view or otherwise aerial/top-down perspective. The level of average participant time to complete the first question is lower in the BEV interactivity mode. The observed average time to answer the question correctly is lower utilizing a BEV environment in every locomotive state. The Sitting/Still and Walking locomotion modes are completed within the BEV environment on average under 60 seconds, and the Teleporting locomotion mode is completed within the BEV environment in under 90 seconds. In every respective locomotive instance, Sitting/Still, Walking, Teleporting, the average time to complete the question within the BEV interactivity mode was above 60

59

seconds, 70 seconds, and 120 seconds. About the question asked, data that requires a full view and exhaustive analysis takes less time to process from a Sitting/Still locomotive state.

The second question asks the user to compare two data points within a given non-changing set of data, to compare two locations within the same year. Within the Sitting/Still mode not much difference is observed in the results. Following Figure 57 participant answer time was more efficient in the GV interactivity mode in the Walking simulation, however, was less efficient within the Teleporting simulation. With data that requires direct comparison between two specific points of said data, the Sitting/Still locomotion mode, averaging under a 40 second answer time, is slightly more efficient than the Teleportation mode, and much more efficient than the Walking mode with an answer time average of just over 40 seconds. However, it is important to note that within this discrepancy, the GV interactivity mode has a less efficient and higher gap in average question time to the BEV interactivity mode when using Teleportation, and a more efficient and smaller gap in average question time to the BEV interactivity mode when using a Sitting/Still locomotive style. Data displayed in a Bird's Eye View manner may not be as effective within restrictive room space.

The third question asks the user to compare two data points within a dynamic, changing set of data, to compare two locations within two separate years. Overall, according to Figure 57 the third question was consistent in average participant question time. This is also the case in the Teleportation locomotion mode, where the BEV interactivity mode is only slightly more efficient than the opposing GV interactivity

mode. A more noticeable difference in the average participant question time can be seen in the Sitting/Still and Walking locomotive states, where the GV interactivity mode appears to be more efficient with an answer time 10 seconds lower than the BEV interactivity mode. Gathering from the data, it appears to be more beneficial to the participant to be immersed in the data when performing data analysis in a restrictive virtual environment where physical room space is limited. The GV Interactivity mode appears to be more beneficial within a restricted space. If teleportation is possible, there does not seem to be any significant difference in performance of the third question asked when implementing infinite velocity techniques.

Figure 40

Interactivity Mode Question Time Average
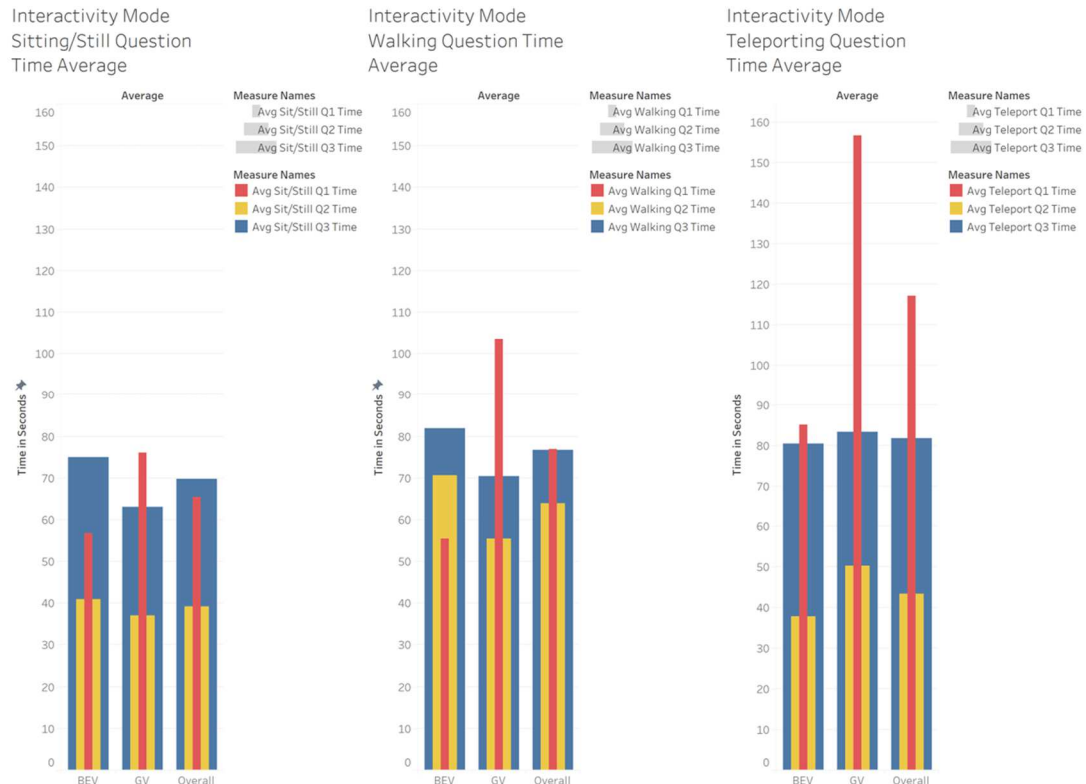
Looking at Figure 58 the standard deviation of users performing the Sitting/Still locomotion mode had slightly better times than the Walking mode, and significantly greater results than the Teleporting mode. The overall standard deviation in the results of each locomotive state in Figure Y is much smaller in a Sitting/Still environment. Participants answering the first question had a standard deviation that was 10 seconds less in the Sitting/Still than the Walking mode, and the Walking mode was 45 seconds less than the Teleporting. The second question had a lower standard deviation in the Sitting/Still by 15 seconds than the Walking mode, which was around the same answer time as the Teleporting mode. The third question as well had a lower standard deviation within the Sitting/Still locomotive state by around 5 seconds compared to the Walking, and by 20 seconds compared to the Teleporting mode. Participants appear to be closer to the average question time across all three questions when placed in a Sitting/Still locomotive state. The only instance where this is not the case is in the instance of the Walking locomotive state while in a bird's eye view perspective. However, the overall standard deviation in the Sitting/Still mode is lower than that of the Walking locomotion.

Figure 41

Interactivity Mode Question Time Standard Deviation
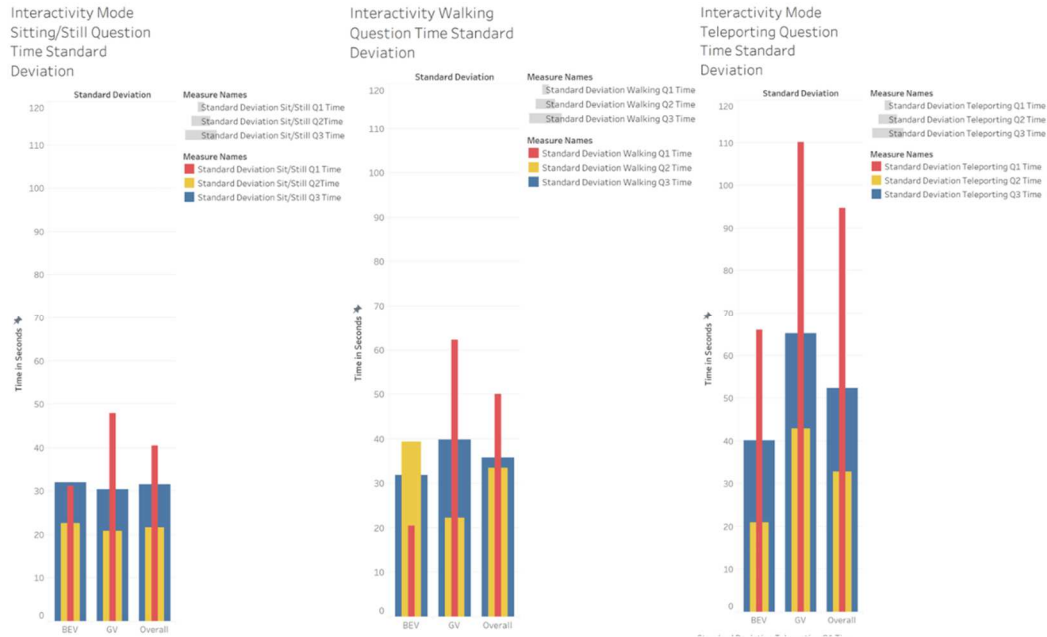
4.2 Gender

Another t-test analysis was conducted on the question times of individual participants split into groups based on their mode of interactivity (BEV or GV) and the participants reported gender (male or female). For each interactivity mode, nine different t-tests were conducted on each question time per locomotive state. Figures 45, 46, and 47 outline the BEV interactivity mode, whereas Figures 48, 49, and 50 outline the GV interactivity mode. In each figure, Variable 1 refers to female participants and Variable 2 refers to male participants.

Figure 42

T-test of Bird's Eye View Sitting/Still Question Times by Gender

t-Test: Two-Sample Assuming Unequal Variances		
SQ1TBEV		
	Variable 1	Variable 2
Mean	55.85133333	57.345625
Variance	1031.172384	985.7815463
Observations	15	16
Hypothesized Mean Difference	0	
df	29	
t Stat	-0.130878881	
P(T<=t) one-tail	0.448387417	
t Critical one-tail	1.699127027	
P(T<=t) two-tail	0.896774835	
t Critical two-tail	2.045229642	
t-Test: Two-Sample Assuming Unequal Variances		
SQ2TBEV		
	Variable 1	Variable 2
Mean	32.246	48.969375
Variance	148.5796257	734.0409529
Observations	15	16
Hypothesized Mean Difference	0	
df	21	
t Stat	-2.239100098	
P(T<=t) one-tail	0.018052115	
t Critical one-tail	1.720742903	
P(T<=t) two-tail	0.03610423	
t Critical two-tail	2.079613845	
t-Test: Two-Sample Assuming Unequal Variances		
SQ3TBEV		
	Variable 1	Variable 2
Mean	79.32133333	70.90125
Variance	1068.138812	1017.789972
Observations	15	16
Hypothesized Mean Difference	0	
df	29	
t Stat	0.725165965	
P(T<=t) one-tail	0.237080755	
t Critical one-tail	1.699127027	
P(T<=t) two-tail	0.47416151	
t Critical two-tail	2.045229642	

Figure 43

T-test of Bird's Eye View Walking Question Times by Gender

t-Test: Two-Sample Assuming Unequal Variances		
WQ1TBEV		
	Variable 1	Variable 2
Mean	55.142	55.8125
Variance	410.5619171	449.90686
Observations	15	16
Hypothesized Mean Difference	0	
df	29	
t Stat	-0.090010158	
P(T<=t) one-tail	0.464448973	
t Critical one-tail	1.699127027	
P(T<=t) two-tail	0.928897946	
t Critical two-tail	2.045229642	
t-Test: Two-Sample Assuming Unequal Variances		
WQ2TBEV		
	Variable 1	Variable 2
Mean	64.35066667	76.225
Variance	960.6121067	2126.6878
Observations	15	16
Hypothesized Mean Difference	0	
df	26	
t Stat	-0.846099712	
P(T<=t) one-tail	0.202608637	
t Critical one-tail	1.70561792	
P(T<=t) two-tail	0.405217275	
t Critical two-tail	2.055529439	
t-Test: Two-Sample Assuming Unequal Variances		
WQ3TBEV		
	Variable 1	Variable 2
Mean	83.63866667	79.981875
Variance	1055.37337	1023.741336
Observations	15	16
Hypothesized Mean Difference	0	
df	29	
t Stat	0.315496263	
P(T<=t) one-tail	0.377322086	
t Critical one-tail	1.699127027	
P(T<=t) two-tail	0.754644171	
t Critical two-tail	2.045229642	

Figure 44

T-test of Bird's Eye View Teleporting Question Times by Gender

t-Test: Two-Sample Assuming Unequal Variances

TQ1TBEV		
	Variable 1	Variable 2
Mean	76.47133333	93.224375
Variance	2195.900727	6518.44688
Observations	15	16
Hypothesized Mean Difference	0	
df	24	
t Stat	-0.71189942	
P(T<=t) one-tail	0.241695189	
t Critical one-tail	1.71088208	
P(T<=t) two-tail	0.483390378	
t Critical two-tail	2.063898562	

t-Test: Two-Sample Assuming Unequal Variances

TQ2TBEV		
	Variable 1	Variable 2
Mean	35.42066667	39.9575
Variance	172.9141352	702.9034867
Observations	15	16
Hypothesized Mean Difference	0	
df	22	
t Stat	-0.609209275	
P(T<=t) one-tail	0.274312984	
t Critical one-tail	1.717144374	
P(T<=t) two-tail	0.548625968	
t Critical two-tail	2.073873068	

t-Test: Two-Sample Assuming Unequal Variances

TQ3TBEV		
	Variable 1	Variable 2
Mean	73.16666667	87.103125
Variance	1011.558338	2178.284996
Observations	15	16
Hypothesized Mean Difference	0	
df	27	
t Stat	-0.976753168	
P(T<=t) one-tail	0.168681145	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	0.337362291	
t Critical two-tail	2.051830516	

Figure 45

T-test of Grounded View Sitting/Still Question Times by Gender

t-Test: Two-Sample Assuming Unequal Variances SQ1TGV		
	Variable 1	Variable 2
Mean	68.63545	81.85214
Variance	891.3247	3472.145
Observations	11	14
Hypothesized Mean Difference	0	
df	20	
t Stat	-0.72862	
P(T<=t) one-tail	0.237341	
t Critical one-tail	1.724718	
P(T<=t) two-tail	0.474683	
t Critical two-tail	2.085963	
t-Test: Two-Sample Assuming Unequal Variances SQ2TGV		
	Variable 1	Variable 2
Mean	37.13182	36.76571
Variance	472.9823	428.1265
Observations	11	14
Hypothesized Mean Difference	0	
df	21	
t Stat	0.04268	
P(T<=t) one-tail	0.48318	
t Critical one-tail	1.720743	
P(T<=t) two-tail	0.96636	
t Critical two-tail	2.079614	
t-Test: Two-Sample Assuming Unequal Variances SQ3TGV		
	Variable 1	Variable 2
Mean	64.21818	62.14429
Variance	692.1458	1164.552
Observations	11	14
Hypothesized Mean Difference	0	
df	23	
t Stat	0.171575	
P(T<=t) one-tail	0.432636	
t Critical one-tail	1.713872	
P(T<=t) two-tail	0.865272	
t Critical two-tail	2.068658	

Figure 46

T-test of Grounded View Walking Question Times by Gender

t-Test: Two-Sample Assuming Unequal Variances		
WQ1TGV		
	Variable 1	Variable 2
Mean	125.6418	85.96571
Variance	4563.956	2898.024
Observations	11	14
Hypothesized Mean Difference	0	
df	19	
t Stat	1.590986	
P(T<=t) one-tail	0.064057	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.128114	
t Critical two-tail	2.093024	
t-Test: Two-Sample Assuming Unequal Variances		
WQ2TGV		
	Variable 1	Variable 2
Mean	50.61545	59.36643
Variance	450.5029	534.5845
Observations	11	14
Hypothesized Mean Difference	0	
df	22	
t Stat	-0.98369	
P(T<=t) one-tail	0.167981	
t Critical one-tail	1.717144	
P(T<=t) two-tail	0.335961	
t Critical two-tail	2.073873	
t-Test: Two-Sample Assuming Unequal Variances		
WQ3TGV		
	Variable 1	Variable 2
Mean	67.90455	72.15571
Variance	483.633	2544.004
Observations	11	14
Hypothesized Mean Difference	0	
df	19	
t Stat	-0.28298	
P(T<=t) one-tail	0.390125	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.78025	
t Critical two-tail	2.093024	

Figure 47

T-test of Grounded View Teleporting Question Times by Gender

t-Test: Two-Sample Assuming Unequal Variances		
WQ1TGV		
	Variable 1	Variable 2
Mean	125.6418	85.96571
Variance	4563.956	2898.024
Observations	11	14
Hypothesized Mean Difference	0	
df	19	
t Stat	1.590986	
P(T<=t) one-tail	0.064057	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.128114	
t Critical two-tail	2.093024	
t-Test: Two-Sample Assuming Unequal Variances		
WQ2TGV		
	Variable 1	Variable 2
Mean	50.61545	59.36643
Variance	450.5029	534.5845
Observations	11	14
Hypothesized Mean Difference	0	
df	22	
t Stat	-0.98369	
P(T<=t) one-tail	0.167981	
t Critical one-tail	1.717144	
P(T<=t) two-tail	0.335961	
t Critical two-tail	2.073873	
t-Test: Two-Sample Assuming Unequal Variances		
WQ3TGV		
	Variable 1	Variable 2
Mean	67.90455	72.15571
Variance	483.633	2544.004
Observations	11	14
Hypothesized Mean Difference	0	
df	19	
t Stat	-0.28298	
P(T<=t) one-tail	0.390125	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.78025	
t Critical two-tail	2.093024	

According to the results of the performed t-tests in the Bird's Eye View regarding gender, the only mode to reject the null hypothesis and show significant differences between gender groups was the Sitting/Still Question 2 Time Bird's Eye View in Figure 45. However, according to the results of the performed t-tests in the Grounded View regarding gender, there are no results which reject the null hypothesis, stating that there are no significant differences between the gender groups in a Grounded View environment. Within a Bird's Eye View environment, there are more significant differences between those who reported gender as male and those who reported gender as female within the second question of a Sitting/Still environment.

Figure 59 shows the averages of participant performance based on self-reported gender. While average times are still close to even, those who identify as female seem to outperform those who identify as male. In the Sitting/Still mode, the Walking mode, and the Teleporting mode, females outperformed males on 2 of the 3 questions asked. Figure 60 shows the standard deviation of participant performance based on self- reported gender. As shown previously in Figure 58, the Sitting/Still locomotive state appears to be the most efficient in terms of the standard deviation being the lowest yield. As seen in Figure 59, this also appears to be the case for the average time it took for participants to answer the questions. There appears to be somewhat of a specific correlation between gender and participant answer time. Between the different modes of locomotion, the specific standard deviation of the participant question time is lower during the more questions within Figure 60 that females outperform males in within the average statistics in the previous figure. While certain questions break this trend, reported gender appears to affect results performed within a 3D environment such as this. Participants who reported their gender as female outperformed males in more question categories during
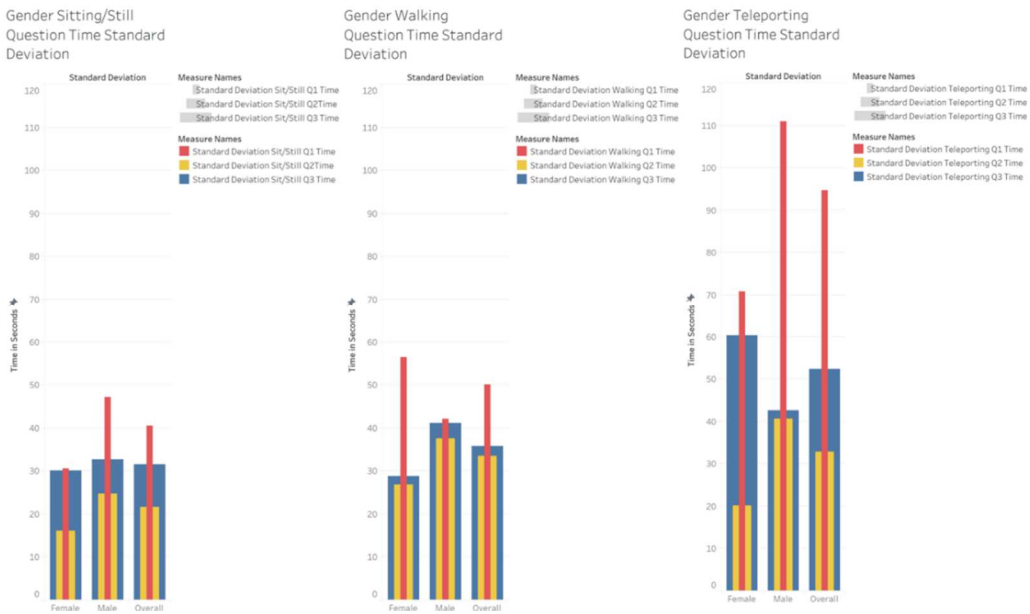
70

the three performed simulations in the VR test.

Figure 48

Gender Question Time Average

Figure 49

Gender Question Time Standard Deviation

4.3 Age

A t-test analysis was conducted on the question times of individual participants split into groups based on their mode of interactivity (BEV or GV) and the participants age (35 and up or under 35). For each interactivity mode, nine different t-tests were conducted on each question time per locomotive state. Figures 39, 40, and 41 outline the BEV interactivity mode, whereas Figures 42, 43, and 44 outline the GV interactivity mode. In each figure, Variable 1 refers to those under the age of 35 and Variable 2 refers to those 35 and over.

According to the results of the performed t-tests in the Bird's Eye View regarding age, there are no results which reject the null hypothesis, stating that there are no significant differences between the age groups in a Bird's Eye View environment. However, within those tested in the Grounded View regarding age, the following modes reject the null hypothesis and show significant differences between the two age groups: Sitting/Still Question 2 Time Grounded View in Figure 42, Walking Question 1 Time Grounded View and Walking Question 2 Time Grounded View in Figure 43, and all three questions for Teleporting Question Time Grounded View in Figure 44. Within a Grounded View environment, there are more significant differences between those 35 and up, and those below the age of 35.

Figure 50

T-test of Bird's Eye View Sitting/Still Question Times by Age

t-Test: Two-Sample Assuming Unequal Variances		
SQ1TBEV		
	Variable 1	Variable 2
Mean	53.90273	63.27111
Variance	949.7046	1092.007
Observations	22	9
Hypothesized Mean Difference	0	
df	14	
t Stat	-0.73043	
P(T<=t) one-tail	0.238587	
t Critical one-tail	1.76131	
P(T<=t) two-tail	0.477174	
t Critical two-tail	2.144787	
t-Test: Two-Sample Assuming Unequal Variances		
SQ2TBEV		
	Variable 1	Variable 2
Mean	42.06591	37.97222
Variance	366.5008	931.5465
Observations	22	9
Hypothesized Mean Difference	0	
df	11	
t Stat	0.373445	
P(T<=t) one-tail	0.357957	
t Critical one-tail	1.795885	
P(T<=t) two-tail	0.715914	
t Critical two-tail	2.200985	
t-Test: Two-Sample Assuming Unequal Variances		
SQ3TBEV		
	Variable 1	Variable 2
Mean	70.77409	85.24556
Variance	879.3639	1370.679
Observations	22	9
Hypothesized Mean Difference	0	
df	12	
t Stat	-1.04366	
P(T<=t) one-tail	0.158607	
t Critical one-tail	1.782288	
P(T<=t) two-tail	0.317213	
t Critical two-tail	2.178813	

Figure 51

T-test of Bird's Eye View Walking Question Times by Age

t-Test: Two-Sample Assuming Unequal Variances
WQ1TBEV

	Variable 1	Variable 2
Mean	56.38091	53.30556
Variance	463.9491	337.0764
Observations	22	9
Hypothesized Mean Difference	0	
df	17	
t Stat	0.401942	
P(T<=t) one-tail	0.346368	
t Critical one-tail	1.739607	
P(T<=t) two-tail	0.692735	
t Critical two-tail	2.109816	

t-Test: Two-Sample Assuming Unequal Variances
WQ2TBEV

	Variable 1	Variable 2
Mean	71.95	66.88444
Variance	2013.912	498.0557
Observations	22	9
Hypothesized Mean Difference	0	
df	28	
t Stat	0.417969	
P(T<=t) one-tail	0.339579	
t Critical one-tail	1.701131	
P(T<=t) two-tail	0.679158	
t Critical two-tail	2.048407	

t-Test: Two-Sample Assuming Unequal Variances
WQ3TBEV

	Variable 1	Variable 2
Mean	72.71409	66.88444
Variance	713.0143	498.0557
Observations	22	9
Hypothesized Mean Difference	0	
df	18	
t Stat	0.62233	
P(T<=t) one-tail	0.270765	
t Critical one-tail	1.734064	
P(T<=t) two-tail	0.541529	
t Critical two-tail	2.100922	

Figure 52

T-test of Bird's Eye View Teleporting Question Times by Age

t-Test: Two-Sample Assuming Unequal Variances TQ1TBEV		
	Variable 1	Variable 2
Mean	84.58091	86.43111
Variance	5216.532	2640.394
Observations	22	9
Hypothesized Mean Difference	0	
df	21	
t Stat	-0.08033	
P(T<=t) one-tail	0.468368	
t Critical one-tail	1.720743	
P(T<=t) two-tail	0.936735	
t Critical two-tail	2.079614	
t-Test: Two-Sample Assuming Unequal Variances TQ2TBEV		
	Variable 1	Variable 2
Mean	38.94682	34.86667
Variance	520.3607	261.2245
Observations	22	9
Hypothesized Mean Difference	0	
df	21	
t Stat	0.562164	
P(T<=t) one-tail	0.289978	
t Critical one-tail	1.720743	
P(T<=t) two-tail	0.579956	
t Critical two-tail	2.079614	
t-Test: Two-Sample Assuming Unequal Variances TQ3TBEV		
	Variable 1	Variable 2
Mean	75.22	92.92333
Variance	1479.896	1907.524
Observations	22	9
Hypothesized Mean Difference	0	
df	13	
t Stat	-1.05946	
P(T<=t) one-tail	0.154339	
t Critical one-tail	1.770933	
P(T<=t) two-tail	0.308678	
t Critical two-tail	2.160369	

Figure 53

T-test of Grounded View Sitting/Still Question Times by Age

t-Test: Two-Sample Assuming Unequal Variances

SQ1TGV		
	Variable 1	Variable 2
Mean	67.478	88.875
Variance	955.7148171	4333.351694
Observations	15	10
Hypothesized Mean Difference	0	
df	12	
t Stat	-0.959738839	
P(T<=t) one-tail	0.178062949	
t Critical one-tail	1.782287556	
P(T<=t) two-tail	0.356125897	
t Critical two-tail	2.17881283	

t-Test: Two-Sample Assuming Unequal Variances

SQ2TGV		
	Variable 1	Variable 2
Mean	29.42266667	48.183
Variance	66.82250667	805.4530456
Observations	15	10
Hypothesized Mean Difference	0	
df	10	
t Stat	-2.034842194	
P(T<=t) one-tail	0.034620976	
t Critical one-tail	1.812461123	
P(T<=t) two-tail	0.069241952	
t Critical two-tail	2.228138852	

t-Test: Two-Sample Assuming Unequal Variances

SQ3TGV		
	Variable 1	Variable 2
Mean	54.682	75.619
Variance	409.6344743	1524.677121
Observations	15	10
Hypothesized Mean Difference	0	
df	12	
t Stat	-1.561520818	
P(T<=t) one-tail	0.072187245	
t Critical one-tail	1.782287556	
P(T<=t) two-tail	0.14437449	
t Critical two-tail	2.17881283	

Figure 54

T-test of Grounded View Walking Question Times by Age

t-Test: Two-Sample Assuming Unequal Variances		
WQ1TGV		
	Variable 1	Variable 2
Mean	78.362	141.015
Variance	957.4102743	6228.307117
Observations	15	10
Hypothesized Mean Difference	0	
df	11	
t Stat	-2.390956137	
P(T<=t) one-tail	0.0179004	
t Critical one-tail	1.795884819	
P(T<=t) two-tail	0.0358008	
t Critical two-tail	2.20098516	

t-Test: Two-Sample Assuming Unequal Variances		
WQ2TGV		
	Variable 1	Variable 2
Mean	47.77333333	67.13
Variance	150.6422238	841.0315333
Observations	15	10
Hypothesized Mean Difference	0	
df	11	
t Stat	-1.994939402	
P(T<=t) one-tail	0.03571017	
t Critical one-tail	1.795884819	
P(T<=t) two-tail	0.07142034	
t Critical two-tail	2.20098516	

t-Test: Two-Sample Assuming Unequal Variances		
WQ3TGV		
	Variable 1	Variable 2
Mean	57.886	88.884
Variance	482.9500543	2832.572049
Observations	15	10
Hypothesized Mean Difference	0	
df	11	
t Stat	-1.745282526	
P(T<=t) one-tail	0.054384233	
t Critical one-tail	1.795884819	
P(T<=t) two-tail	0.108768465	
t Critical two-tail	2.20098516	

Figure 55

T-test of Grounded View Teleporting Question Times by Age

t-Test: Two-Sample Assuming Unequal Variances		
TQ1TGV		
	Variable 1	Variable 2
Mean	113.9206667	220.761
Variance	3412.763007	19442.30848
Observations	15	10
Hypothesized Mean Difference	0	
df	11	
t Stat	-2.292611577	
P(T<=t) one-tail	0.021290851	
t Critical one-tail	1.795884819	
P(T<=t) two-tail	0.042581701	
t Critical two-tail	2.20098516	
t-Test: Two-Sample Assuming Unequal Variances		
TQ2TGV		
	Variable 1	Variable 2
Mean	35.66666667	72.327
Variance	319.0892952	3503.115779
Observations	15	10
Hypothesized Mean Difference	0	
df	10	
t Stat	-1.90181291	
P(T<=t) one-tail	0.043181922	
t Critical one-tail	1.812461123	
P(T<=t) two-tail	0.086363843	
t Critical two-tail	2.228138852	
t-Test: Two-Sample Assuming Unequal Variances		
TQ3TGV		
	Variable 1	Variable 2
Mean	61.07666667	116.42
Variance	455.7569952	8563.647467
Observations	15	10
Hypothesized Mean Difference	0	
df	10	
t Stat	-1.85851072	
P(T<=t) one-tail	0.046370702	
t Critical one-tail	1.812461123	
P(T<=t) two-tail	0.092741403	
t Critical two-tail	2.228138852	

Looking at Figure 61, the results indicate that users that are over the age of 35 perform on average less efficiently than those who are younger than 35. However, if we look at the standard deviation in Figure 62, the variation among older participants is much higher in most questions, other than the Walking locomotion mode. Comparing the two charts above, Figure A and B, the average participant time compared to the standard deviation shows that there is a higher variation of results within older individuals. Younger participants under the age of 35 appear to have a tighter deviation with ability, and the demographic of people over 35 tested has a wider range of results.

Figure 56

Age Question Time Average
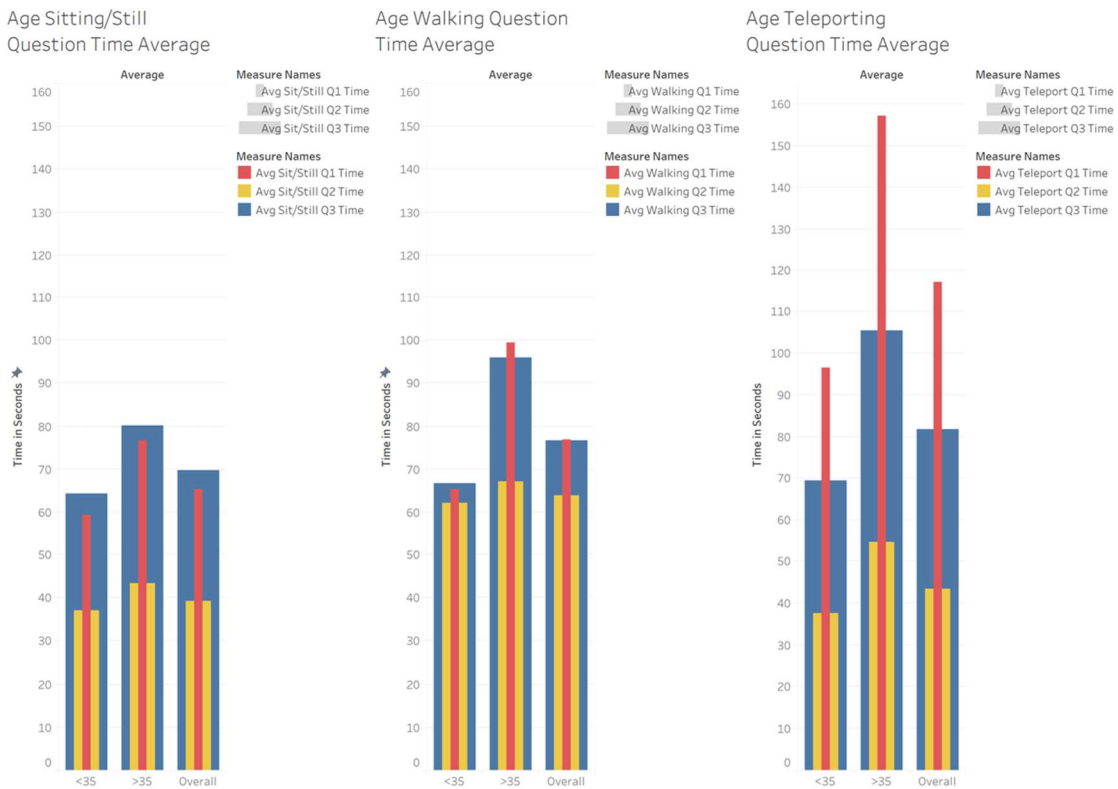
Figure 57

Age Question Time Standard Deviation
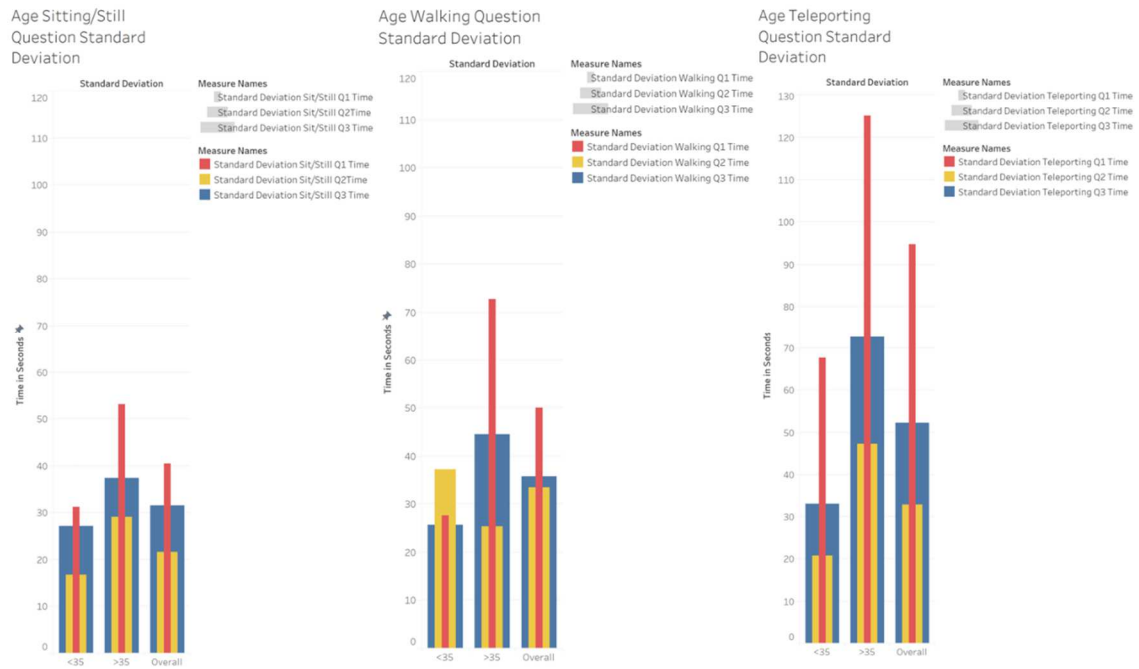
4.4 Spatial Ability

The spatial ability of each user was tested within the cube score test to see if an individual's spatial ability had any effect on answer time. According to Figures 63 and 64, the demographic with both the highest average spatial ability and lowest standard deviation was the group of individuals under 35, as seen by the red coloration in Figure 63 and the blue coloration in Figure 64 above <35. The demographic that was completely opposite of this, was the group of individuals consisting of over 35, as observed above the >35 in both Figures 63 and 64. Looking at Figure 64 there is a lower variance from the mean from Female subjects compared to the male subjects, where the average cube score appears to be the same from male to female. Participants who are included in the <35 age group have higher spatial ability scores and lower variance than the respective

>35 counterpart, however, the observed standard deviation shows that the average spatial ability scores of males and females were the same even though the standard deviation shows that more females are closer to the average than males. Questions that challenge a certain interactivity mode or locomotive state seem to be affected by one's spatial ability, however, there appear to be certain characteristics associated with spatial ability and age or gender.

Observed in Figure 65 is every participant with the question time of each of the nine questions answered. Each datapoint is colored to represent the cube score of each participant. The darker colored points tend to gather below with lower question time where the higher points have a lighter color indicating low spatial ability gathered from the participant. Even though the observed points that are higher in question time have lower spatial ability, it appears that those with low spatial ability still can perform well during the questions. This can be explained by the variance of performance in age as observed in Figures 63 and 64. So, the spatial ability of a user does not necessarily affect how well the user will perform, however age seems to play a more significant role in affecting the question time of a participant.

Figure 58

Cube Score Question Time Average

Figure 59

Cube Score Question Time Standard Deviation
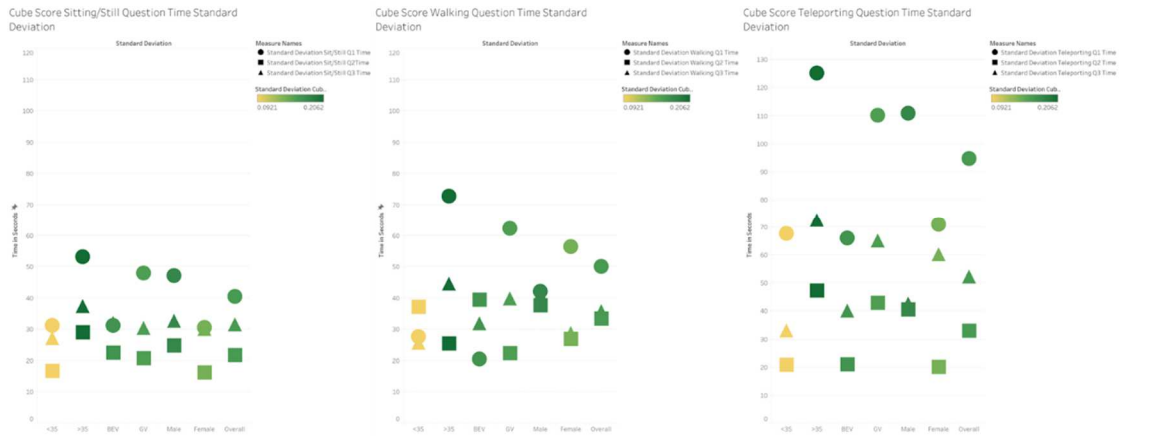
Figure 60

Participant Question Time vs. Participant Cube Score
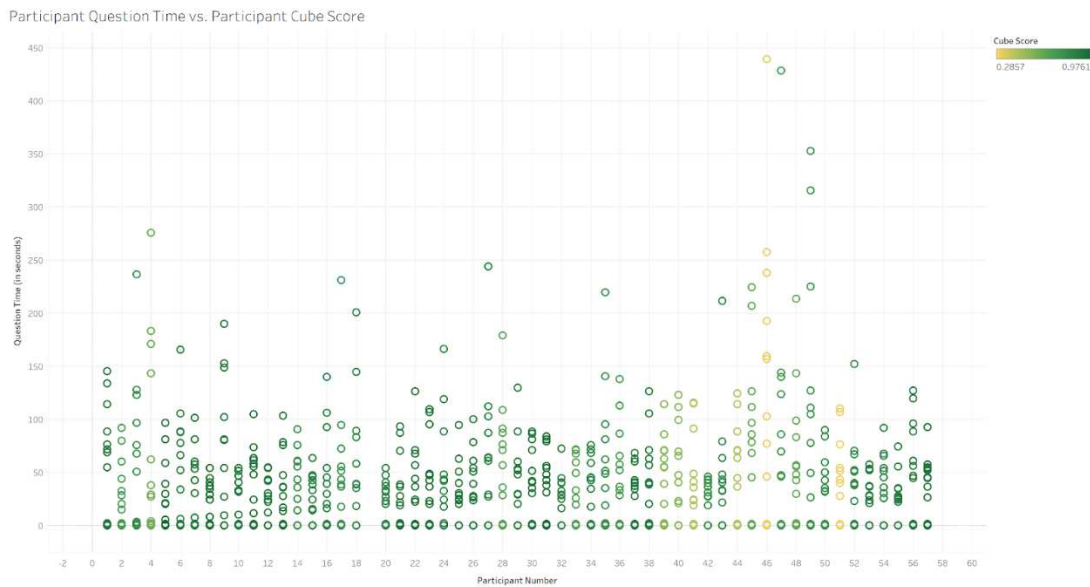
4.5 Game/VR Experience

A final round of t-test analysis was conducted on the question times of individual participants split into groups based on their experience with VR. Because the users were prompted to answer on a 1-5 scale range, from Never to Always, the experiences of those using VR were split into two groups consisting of: Never and Rarely responses, and then Sometimes, Most of the Time, and Always responses. For each interactivity mode, nine different t-tests were conducted on each question time per locomotive state. Figures 51, 52, and 53 outline the BEV interactivity mode, whereas Figures 54, 55, and 56 outline the GV interactivity mode. In each figure, Variable 1 refers to little VR experience in participants and Variable 2 refers to some VR experience in participants.

Figure 61

T-test of Bird's Eye View Sitting/Still Question Times by VR Experience

t-Test: Two-Sample Assuming Unequal Variances		
SQ1TBEV		
	Variable 1	Variable 2
Mean	60.90577	34.35
Variance	1039.803	72.0072
Observations	26	5
Hypothesized Mean Difference	0	
df	26	
t Stat	3.600675	
P(T<=t) one-tail	0.000656	
t Critical one-tail	1.705618	
P(T<=t) two-tail	0.001312	
t Critical two-tail	2.055529	
t-Test: Two-Sample Assuming Unequal Variances		
SQ2TBEV		
	Variable 1	Variable 2
Mean	43.58308	26.808
Variance	539.0548	149.8696
Observations	26	5
Hypothesized Mean Difference	0	
df	11	
t Stat	2.355762	
P(T<=t) one-tail	0.019049	
t Critical one-tail	1.795885	
P(T<=t) two-tail	0.038098	
t Critical two-tail	2.200985	
t-Test: Two-Sample Assuming Unequal Variances		
SQ3TBEV		
	Variable 1	Variable 2
Mean	75.55923	71.94
Variance	1193.514	219.2245
Observations	26	5
Hypothesized Mean Difference	0	
df	14	
t Stat	0.382033	
P(T<=t) one-tail	0.354087	
t Critical one-tail	1.76131	
P(T<=t) two-tail	0.708173	
t Critical two-tail	2.144787	

Figure 62

T-test of Bird's Eye View Walking Question Times by VR Experience

t-Test: Two-Sample Assuming Unequal Variances
WQ1TBEV

	Variable 1	Variable 2
Mean	55.04077	57.814
Variance	395.2563	646.5727
Observations	26	5
Hypothesized Mean Difference	0	
df	5	
t Stat	-0.23069	
P(T<=t) one-tail	0.413349	
t Critical one-tail	2.015048	
P(T<=t) two-tail	0.826698	
t Critical two-tail	2.570582	

t-Test: Two-Sample Assuming Unequal Variances
WQ2TBEV

	Variable 1	Variable 2
Mean	77.31115	34.954
Variance	1517.586	244.2727
Observations	26	5
Hypothesized Mean Difference	0	
df	16	
t Stat	4.090556	
P(T<=t) one-tail	0.000427	
t Critical one-tail	1.745884	
P(T<=t) two-tail	0.000853	
t Critical two-tail	2.119905	

t-Test: Two-Sample Assuming Unequal Variances
WQ3TBEV

	Variable 1	Variable 2
Mean	86.84115	55.284
Variance	979.3471	393.7582
Observations	26	5
Hypothesized Mean Difference	0	
df	8	
t Stat	2.924733	
P(T<=t) one-tail	0.009576	
t Critical one-tail	1.859548	
P(T<=t) two-tail	0.019152	
t Critical two-tail	2.306004	

Figure 63

T-test of Bird's Eye View Teleporting Question Times by VR Experience

t-Test: Two-Sample Assuming Unequal Variances		
TQ1TBEV		
	Variable 1	Variable 2
Mean	91.30577	52.942
Variance	4916.278	403.3182
Observations	26	5
Hypothesized Mean Difference	0	
df	24	
t Stat	2.335821	
P(T<=t) one-tail	0.014093	
t Critical one-tail	1.710882	
P(T<=t) two-tail	0.028185	
t Critical two-tail	2.063899	
t-Test: Two-Sample Assuming Unequal Variances		
TQ2TBEV		
	Variable 1	Variable 2
Mean	39.93231	26.478
Variance	484.2274	64.72677
Observations	26	5
Hypothesized Mean Difference	0	
df	18	
t Stat	2.39457	
P(T<=t) one-tail	0.013867	
t Critical one-tail	1.734064	
P(T<=t) two-tail	0.027734	
t Critical two-tail	2.100922	
t-Test: Two-Sample Assuming Unequal Variances		
TQ3TBEV		
	Variable 1	Variable 2
Mean	85.40346	54.132
Variance	1732.608	230.9227
Observations	26	5
Hypothesized Mean Difference	0	
df	18	
t Stat	2.944075	
P(T<=t) one-tail	0.004339	
t Critical one-tail	1.734064	
P(T<=t) two-tail	0.008677	
t Critical two-tail	2.100922	

Figure 64

T-test of Grounded View Sitting/Still Question Times by VR Experience

t-Test: Two-Sample Assuming Unequal Variances
SQ1TGV

	Variable 1	Variable 2
Mean	78.38045455	58.85
Variance	2557.335757	208.0567
Observations	22	3
Hypothesized Mean Difference	0	
df	11	
t Stat	1.433604933	
P(T<=t) one-tail	0.089746186	
t Critical one-tail	1.795884819	
P(T<=t) two-tail	0.179492372	
t Critical two-tail	2.20098516	

t-Test: Two-Sample Assuming Unequal Variances
SQ2TGV

	Variable 1	Variable 2
Mean	37.50272727	32.70333333
Variance	481.759716	59.26443333
Observations	22	3
Hypothesized Mean Difference	0	
df	8	
t Stat	0.743641057	
P(T<=t) one-tail	0.239181303	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	0.478362606	
t Critical two-tail	2.306004135	

t-Test: Two-Sample Assuming Unequal Variances
SQ3TGV

	Variable 1	Variable 2
Mean	65.87409091	42.39666667
Variance	974.0948348	87.99643333
Observations	22	3
Hypothesized Mean Difference	0	
df	10	
t Stat	2.73643068	
P(T<=t) one-tail	0.010480384	
t Critical one-tail	1.812461123	
P(T<=t) two-tail	0.020960769	
t Critical two-tail	2.228138852	

Figure 65

T-test of Grounded View Walking Question Times by VR Experience

t-Test: Two-Sample Assuming Unequal Variances
WQ1TGV

	Variable 1	Variable 2
Mean	108.2622727	67.93666667
Variance	4158.792409	691.6049333
Observations	22	3
Hypothesized Mean Difference	0	
df	6	
t Stat	1.9686938	
P(T<=t) one-tail	0.048262416	
t Critical one-tail	1.943180281	
P(T<=t) two-tail	0.096524832	
t Critical two-tail	2.446911851	

t-Test: Two-Sample Assuming Unequal Variances
WQ2TGV

	Variable 1	Variable 2
Mean	56.67181818	47.04
Variance	527.596168	300.9604
Observations	22	3
Hypothesized Mean Difference	0	
df	3	
t Stat	0.863912199	
P(T<=t) one-tail	0.22559001	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.45118002	
t Critical two-tail	3.182446305	

t-Test: Two-Sample Assuming Unequal Variances
WQ3TGV

	Variable 1	Variable 2
Mean	71.35409091	62.44666667
Variance	1625.885949	1833.318433
Observations	22	3
Hypothesized Mean Difference	0	
df	3	
t Stat	0.340332689	
P(T<=t) one-tail	0.378021642	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.756043284	
t Critical two-tail	3.182446305	

Figure 66

T-test of Grounded View Teleporting Question Times by VR Experience

t-Test: Two-Sample Assuming Unequal Variances
TQ1TGV

	Variable 1	Variable 2
Mean	159.6372727	134.8
Variance	12978.44655	8536.3159
Observations	22	3
Hypothesized Mean Difference	0	
df	3	
t Stat	0.423757377	
P(T<=t) one-tail	0.350145344	
t Critical one-tail	2.353363435	
P(T<=t) two-tail	0.700290688	
t Critical two-tail	3.182446305	

t-Test: Two-Sample Assuming Unequal Variances
TQ2TGV

	Variable 1	Variable 2
Mean	52.97681818	30.92666667
Variance	1993.272899	458.4246333
Observations	22	3
Hypothesized Mean Difference	0	
df	5	
t Stat	1.413321643	
P(T<=t) one-tail	0.10834207	
t Critical one-tail	2.015048373	
P(T<=t) two-tail	0.21668414	
t Critical two-tail	2.570581836	

t-Test: Two-Sample Assuming Unequal Variances
TQ3TGV

	Variable 1	Variable 2
Mean	86.63227273	58.14666667
Variance	4730.372266	175.3701333
Observations	22	3
Hypothesized Mean Difference	0	
df	19	
t Stat	1.722533728	
P(T<=t) one-tail	0.050605674	
t Critical one-tail	1.729132812	
P(T<=t) two-tail	0.101211347	
t Critical two-tail	2.093024054	

According to the results of the performed t-tests in the Bird's Eye View in regards to VR Experience, the following modes had significant differences between the two groups of VR Experience: Sitting/Still Question 1 Time Bird's Eye View and Sitting/Still Question 2 Time Bird's Eye View in Figure 51, Walking Question 1 Time Bird's Eye View and Walking Question 2 Time Bird's Eye View in Figure 52, and every question in Teleporting Question Time Bird's Eye View Figure 53. According to the results of the performed t-tests in the Grounded View regarding VR Experience, the following modes had significant differences between the two groups of VR Experience: Sitting/Still Question 1 Time Grounded View in Figure 54 and Walking Question 1 Time Grounded View in Figure 55. Within a Bird's Eye View environment, there are more significant differences between groups of individuals with little VR Experience compared to those more familiar with VR.

Figures 66 and 67 show the Game and VR Experience of users compared to the time it took to answer the question. While game experience does not appear to produce any sort of significant trend to using the tool, VR experience seems to affect the results as well. Participants that had previous experience appear to have a much easier time utilizing the tool and answering questions faster than those who rarely or never use VR.

Figure 67

Participant Question Time vs. Game Experience

Participant Question Time vs. Game Experience
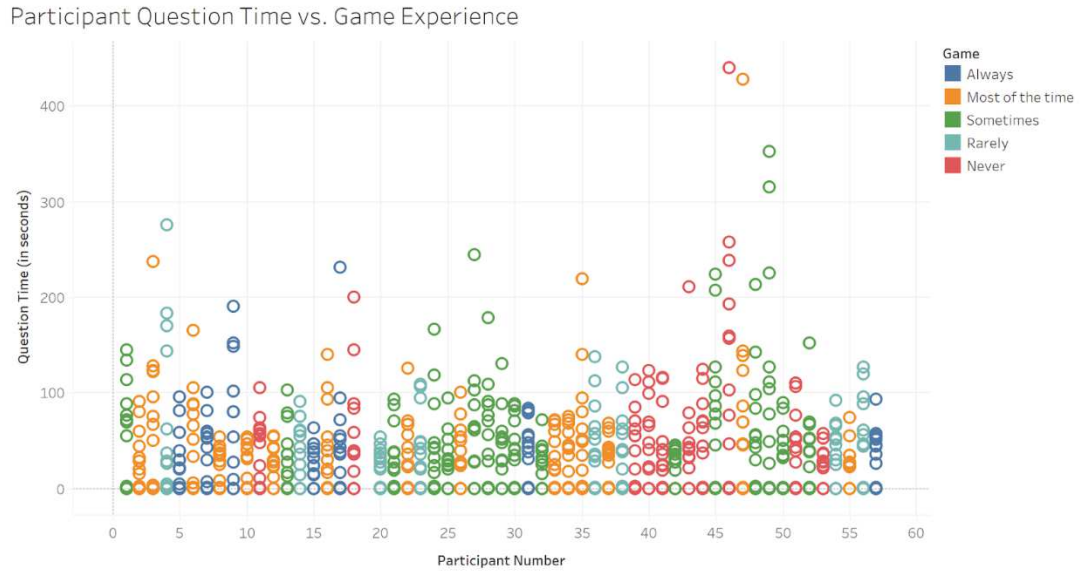
Figure 68

Participant Question Time vs. VR Experience

Participant Question Time vs. VR Experience
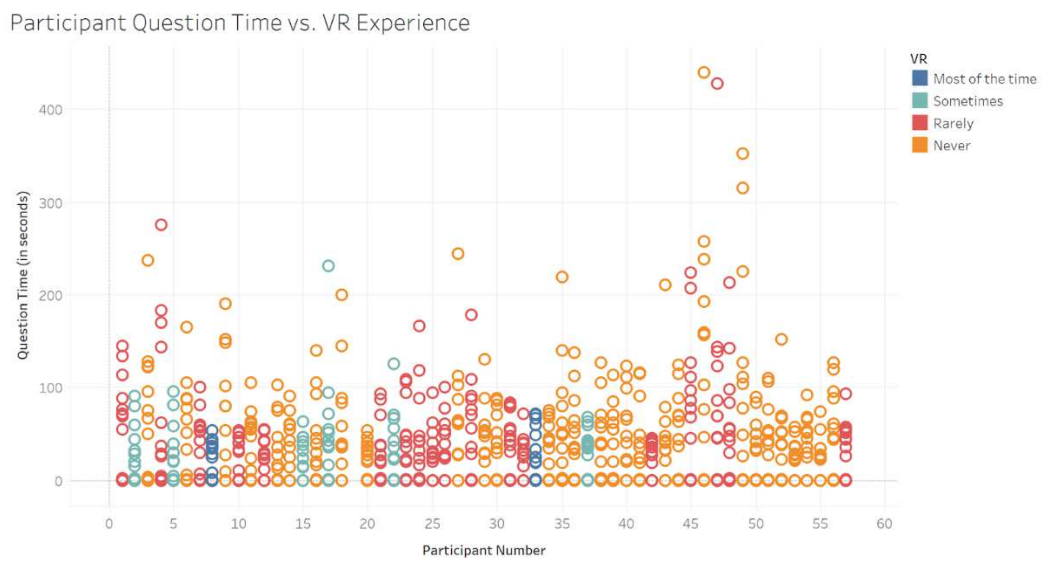
4.6 Participant Feedback

The following is an outline of the user feedback provided in the exit survey. Comments, concerns, or anything that the participant wanted to express was able to do so in the exit survey.

Across both interactivity modes, participants seemed to have split feelings on the use of the rotation and zoom functions. The users that seemed to have a handle on the functionality benefited, however those that did not seemed to not care to utilize the features as it was a hindrance to their ease in answering the questions. However, users speak highly of the teleportation gesture and the save gesture. They expressed that these gestures were natural and that helped them both perform the gestures as well as navigate the data in an efficient and comfortable manner.

Even though many say the gesture to teleport felt natural and easy to use, across both interactivity modes participants expressed mixed feelings about the gesture's effectiveness within the given simulation. Users that did not prefer the teleportation gesture mentioned that they preferred to sit still or view the data through walking, whereas those who preferred teleportation did not often give a reason why they disliked the other modes of locomotion. However, overall, there was a general praise with the ease of use, learning, and natural feel to the simulations from the participant feedback.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The design of an effective immersive workspace is important to pinpoint, especially if being introduced to a setting that is largely unfamiliar with the new field of immersive analytics. Those who had previous VR experience performed better than those that did not, even though the mechanics in controlling the device were different.

According to the initial T-test results performed on the two age groups, within the Grounded View environment, there were more significant differences between those 35 and up, and those below the age of 35. In the T-tests performed on the two gender groups, within the Bird's Eye View environment, there were more significant differences between those who reported gender as male and those who reported gender as female within the second question of a Sitting/Still environment. And within the final round of T-tests on the VR experience of participants, within the Bird's Eye View environment, there were more significant differences between groups of individuals with little VR Experience compared to those more familiar with VR.

Participants that were faced with situations where all the given data in a dataset must be interpreted takes less time from a Sitting/Still locomotive state. Even though the complexity of each question is different, when placed in a Sitting/Still environment participants perform closer to the average question time across all three of those

questions asked. In simulation states where the data is poised in a similar manner to the

Grounded View interactivity mode, utilizing a static method of locomotion is optimal to

one that encourages the participant to navigate the virtual environment. Results also show

that it is more beneficial to the participant to be immersed in the data when performing

analysis on the dataset in a restrictive virtual environment, given that the physical space

is limited. This can tell us that when using a Sitting/Still locomotive mode within an

immersive analytics platform a participant most benefits from that platform when they

are immersed within the dataset and can view said dataset from a static position, such as

sitting or standing still.

The questions are designed to challenge the given interactivity mode and

locomotive states that participants perform seem to be affected by the spatial ability of

that participant, however the spatial ability of a participant may be influenced by age or

gender. In terms of reported gender identity participants who reported their gender as

female outperformed males in more question categories during the three performed

simulations in the VR test. As for tested age groups, the variation of results in participant

time was higher within older participants. According to results it appears the age of a

participant plays a significant role in the spatial ability of a participant, which in turn

would affect the question time. So, the spatial ability of a given participant doesn't

necessarily affect how well a user will perform. The age of the individual participant

seems to play a larger role in the question time answered than the spatial ability of the

individual participant.

The following research questions from Chapter 3: Research Goals are addressed as follows.

1. *In what ways can a user navigate through an immersive space, and which is most effective?*

In an immersive analytics platform, which utilizes hand-tracking technology, users are able to navigate through immersive spaces through static navigation, like sitting still and rotating represented by the Sitting/Still locomotive mode. Physical navigation which produces smooth locomotion, like walking represented by the Walking locomotive mode. Or through infinite velocity techniques like teleporting, which require some control (or in this case, a hand-gesture) represented by the Teleporting locomotive mode. **The most effective of these modes of locomotion from the results is the Sitting/Still Locomotive State.**

2. *In what ways can a user interact with 3D data visualizations in an immersive space, and which is most effective?*

The two ways in which a user may interact with 3D data visualizations is through immersion, represented via the Grounded View interactivity mode. And the god-like view or aerial view, represented via the Bird's Eye View interactivity mode. According to results and participant feedback, users who performed while immersed within the data appeared to be more efficient than those viewing data from an aerial point

of view. **The more effective interactivity mode between the two is the Grounded View.**

3. *Which combination of locomotion and interactivity appears to be the most effective?*

According to the results, within an immersive analytics platform a user benefits most from utilizing a **Sitting/Still locomotive state within a Grounded View interactivity mode.**

4. *Does the utilization of hand gestures via hand-tracking to manipulate data increase effectiveness?*

Participant feedback shows mixed feelings on using hand-gestures to perform data manipulation via the rotation and resize functions and preferred to navigate through or above the data. However, participants reported an ease-of-use and learning with using the hand-gestures that aided movement in the teleporting mode, as well as utilizing the save feature and working with the control panel. **Effectiveness of an immersive analytics platform increases when utilizing natural hand-gestures in concurrence with physical or virtual navigation.**

5. *Does the spatial ability of a user affect the outcome of using immersive analytics?*

   While results show that factors such as spatial ability and gender do not affect the outcome of using an immersive analytics platform, age seems to carry variance within the reported question times and plays a role in exploring the data. **Spatial ability of a user does not affect the outcome of using immersive analytics, but age and gender do.**

1. *Do human factors, such as age, gender, and the VR Game Experience of a user affect the outcome of using immersive analytics?*

   Users who have experience with VR in the past perform more effectively within an immersive analytics platform than those who have little experience.

5.2 Future Work

In future work, it is hoped that newer generations of VR HMDs are utilized in testing to avoid issues that the participants may face such as cords that hinder movement, fickle cameras, and graphical shortcomings. The limitations of the Leap Motion Controller's tracking could also be improved upon to allow users to perform hand

gestures with any arm positioning, and not just in front of the camera placed in front of the VR HMD. Hopefully this research will contribute to future research in the field of immersive analytics and the utilization of hand tracking technology in concurrence with 3DUI components.

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